Eos

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SCIENCE NEWS BY AGU

FILLING IN THE MARGINS

This spring, GeoPRISMS leaves behind a legacy of research by shoreline-crossing scientists and the National Science Foundation.

Supercharged Lightning

An Asteroid Double Disaster

Sooty Stalagmite Records

AGU
ADVANCING EARTH AND SPACE SCIENCE

Crossing the Shoreline

They were going to meet in San Francisco last December to celebrate the end of an era. Then the community of scientists behind GeoPRISMS had to make the same adjustments all of us did and had to move those toasts into this spring. But they nevertheless gathered for virtual sessions at AGU's Fall Meeting 2020 to take a look at the legacy they created in a set of oral sessions titled "Advances in Understanding Continental Margin Evolution: Two Decades of GeoPRISMS and MARGINS Science."

That community actually sprung up not 2 but more than 3 decades ago, when a group met in 1988 to discuss how Earth scientists and ocean scientists could better work together. In response, the Earth Sciences and Ocean Sciences divisions of the National Science Foundation (NSF) teamed up to fund MARGINS, launched in 2000. Its success led to a 10-year successor program called Geodynamic Processes at Rifting and Subducting Margins, or GeoPRISMS. This issue of *Eos* looks at these impressive initiatives as they come to a close this year.

Anaïs Férot, the GeoPRISMS science coordinator at NSF, writes more about this history on page 20. Over these few decades, the programs have developed not only a successful model for producing good science but one that produces good *scientists.* The community made a dedicated effort to support early-career and diverse researchers and regularly participated in education and outreach through initiatives like the GeoPRISMS Distinguished Lectureship Program, sending speakers to colleges, museums, and other public venues.

Férot connected us with the scientists featured in this issue who have provided just a small glimpse into the volume of research GeoPRISMS has produced. On page 22, Noel Bartlow and colleagues take us on a world tour of the "Slipping and Locking in Earth's Earthquake Factories," from the Nankai Trough off southwestern Japan to the Middle America Trench beneath Costa Rica and several others. Bartlow et al. describe what the differences and commonalities between these locations tell us about earthquake processes and how new studies can continue this work started by MARGINS and GeoPRISMS.

We switch from movement of the ground to movement of water and gases with James D. Muirhead and colleagues in "Earth's Volatile Balancing Act," page 28. Understanding how carbon dioxide, sulfur dioxide, and water circulate between the ocean, atmosphere, and minerals in Earth gives us crucial information about the planet's tectonic and volcanic processes and our climate. Finally, on page 34, Lindsay L. Worthington and colleagues describe the long—much longer than previously thought—process it took for Africa and North America to split.

Thanks also go to Michelle Coombs, with the Volcano Science Center at the U.S. Geological Survey, who let us use her photo of lava flow on Kanaga Island in Alaska for our cover. Her image won first place in 2017 in an annual photo contest held by the GeoPRISMS program.

Do you have an amazing photo from the field or lab? Send it to us at bit.ly/Eos-postcard, and we may feature it in *Postcards from the Field.* Usually, you'll find these beautiful contributions on our final page, but in this issue we are very excited to bring you another crossword puzzle—fitting in with our theme of geoprocesses—by Russ Colson, Minnesota State University Moorhead. Enjoy!

Heather Goss, Editor in Chief

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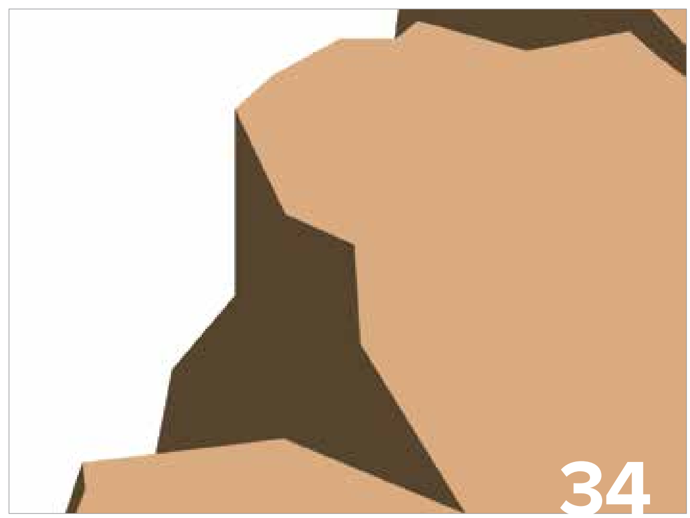

Features

On the Cover

Blocky lava flow leads back to Kanaga Volcano on Kanaga Island, part of the Aleutian Arc. The Alaska-Aleutian subduction zone is one of five primary sites studied under the GeoPRISMS science plan. Credit: M. L. Coombs/Alaska Volcano Observatory/USGS

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Coastal Erosion by Waves Versus Rainfall

Coastal cliffs are vulnerable to erosion, and multiple serious collapses have occurred in California in recent years. Scientists have succeeded in quantifying and separating erosional effects caused by ocean waves from erosion due to rainfall. The team conducted more than 150 lidar surveys of the study site in Del Mar over a 3-year period.

Although there have been numerous studies examining the causes of erosion in rocky coastal bluffs, research that manages both to separate wave effects from precipitation effects and to quantify them is rare. Adam Young, a coastal geomorphologist at the Scripps Institution of Oceanography and lead author of the new study, chalks this up to how infrequently cliff data are usually gathered. "Typically, we only had one or two lidar surveys a year," Young said. "Those are great, but they only provide seasonally averaged information."

Data collected at only seasonal timescales are a problem when you're trying to tease out the details of cliff erosion processes. "In studies of coastal systems, especially those that change regularly, like beaches and cliffs, it really pays off to measure them frequently," explained Jonathan Warrick, a research geologist with the U.S. Geological Survey who was not part of the new study. This problem with seasonal timescales is particularly relevant in places like Southern California, where, as Young noted, "both rainfall and increased wave action occur in the winter. Therefore, higher frequency surveys that capture individual rainfall and large wave events are needed to separate and quantify how these processes drive cliff erosion."

Erosion threatens cliffs in Southern California's Torrey Pines State Natural Preserve. Visitors are warned to stay at least 10 feet away from the cliff base to avoid injuries in the event of a collapse. Credit: iStockPhoto.com/Aaron Hawkins

For their new study, published in the journal *Geomorphology,* Young and his research team mapped a 2.5-kilometer (1.5-mile) stretch of cliffs and adjacent beaches an average of once per week for 3 years (bit.ly/coastal-cliff-erosion). The researchers gathered the bulk of their richly detailed data set by using a truck-mounted lidar system. They drove slowly along the beach in multiple passes, aiming the lidar system at different angles to precisely capture all the variations of the cliff face and the beach elevation. They supplemented their lidar data with wave pressure sensors they buried along the beach, as well as with rainfall data provided by their local weather station and data from the nearby La Jolla tide gauge.

New Findings from Improved Data Collection

The combination of more frequent data collection and a better remote sensing system—the researchers' truck-mounted lidar system was an upgrade from GPS and the all-terrain vehicles they had previously been using—enabled the scientists to quantify the relationships between wave-driven and rainfall-driven cliff erosion. Their analyses of the data found that erosion of the lower part of the cliff was more strongly correlated with wave impacts and that rainfall was more closely correlated with erosion of the upper cliff.

"In our coastal [research] community, we've long asked the question about why cliff change occurs and what are the driving forces," Warrick said. He explained that although scientists have understood that "ocean- and land-based processes" are the primary processes that contribute to cliff failure, "it's been challenging to measure those competing processes and compare them." Speaking about Young's findings, Warrick stated, "[This study] really helps us answer some of those questions that we've been asking for decades in our field. And one of the neat things about it is that it showed it's not an either-or question. It's not a question about whether it's waves or hydrology [eroding a cliff]. These two dominant processes are working together."

"With the relationships quantified in this study, we can estimate how much erosion is going to occur for a particular storm forecast at the study site."

Being able to distinguish between wave effects and rainfall effects is important when it comes to modeling and forecasting cliff erosion, Young explained. "Currently, most models use either waves or rainfall to drive cliff erosion, but usually not combined together. In many locations such as Southern California, both processes are important." He clarified by email, "With the relationships quantified in this study, we can estimate how much erosion is going to occur for a particular storm forecast at the study site." Young also specified that this new information enables scientists to forecast how high on the cliff's profile the erosion from an incoming storm is likely to occur.

The team's work could also be influential for cliff modeling that looks at longer timescales, such as projecting how quickly and how far coastal cliffs will retreat. As Warrick explained, "having an understanding like this and quantifying it is essential for [cliff change] forecasts. Ultimately, we would like to know how much erosion [to expect] over the next century—whether it is ten meters or a hundred meters—and these studies are going to help us do those forecasts in the future."

The new study was funded by the California Department of Parks and Recreation and by the U.S. Army Corps of Engineers.

By **Jady Carmichael** (@jadycarmichael), Science Writer

Dust on the Wind

Scientists studied dust in this sediment core, cut lengthwise here, drilled from the floor of the North Pacific Ocean to assess changing patterns in the westerly winds. Credit: Jordan Abell/Lamont-Doherty Earth Observatory

From the 15th to the 17th century, European sailors rode prevailing winds known as the westerlies to reach lucrative spice markets in Southeast Asia. This powerful atmospheric system, which blows west to east around Earth's middle latitudes, also brought prosperity to the ancient kingdom of Loulan on China's Silk Road by way of consistent rain to feed its crops.

In addition to ships and moisture, the westerlies transport dust, sometimes over astonishingly long distances. In 2003, scientists traced particles carried by westerlies from China's Taklamakan Desert to the French Alps. Much of the westerlies' dust, however, drops into the northern Pacific Ocean, which is why scientists at Columbia University's Lamont-Doherty Earth Observatory thought that might be the place to look for concrete evidence to confirm that the westerlies are shifting toward the poles as the climate warms.

A number of researchers have posited that the westerlies may be shifting, based on computer modeling and satellite data showing changes to ocean currents. Those data sets however, don't go back very far. "It's hard to differentiate natural variability from longer-term trends with just several decades' worth of data," said Jordan Abell, a doctoral student in Earth and environmental sciences at Lamont-Doherty.

So Abell, his mentor Gisela Winckler, and their colleagues decided to go back to the Pliocene. "At first, it might sound a little weird, right?" said Winckler, an isotope geochemist at Lamont-Doherty. "You have to go back 3 million years?" But, she said, that time period mirrors the carbon dioxide levels that exist on Earth now, along with temperature levels similar to those Earth may face in a few decades if it continues to warm—2°C–4°C higher than today's levels.

Although there are no Pliocene wind records, there are records of millions of years' worth of dust that have piled up on the ocean floor. The team analyzed two 8-meter-long sediment cores from two places in the North Pacific Ocean at about the 36th and 45th parallels.

> **"At first, it might sound a little weird, right? You have to go back 3 million years?"**

Temperature Extremes Led to Wind Shifts

The researchers also looked at one particular point in time, 2.73 million years ago. The Pliocene was waning, Earth was cooling, and the Pleistocene ice age, with its woolly mammoths and saber-toothed cats, was starting to take hold. During ice ages like the Pleistocene, both the tropics and the poles got colder. The temperature drop at the poles, however, was much greater—around 6°C – 10°C compared with 2°C at the equator, explained Timothy D. Herbert, a coauthor and professor of Earth, environmental, and planetary sciences at Brown University. That temperature difference would have led to differences in air pressure as well as ultimately making the westerlies stronger and shifting them toward the equator.

But how to prove that? Abell and colleagues knew that if the westerlies did indeed move toward the tropics as Earth got colder, they should find a higher percentage of dust at the more southerly 36th parallel than at the 44th parallel—and they did.

"I think it's a clever way of using a climate proxy—dust preserved in two marine sediment cores at different latitudinal positions—to try and tease apart how the westerly wind belt shifted during these large-scale climate transitions," said Sarah Aarons, an isotope geochemist at Scripps Institution of Oceanography who was not involved in the study. "And ultimately, I think it's important...because scientists will be able to incorporate that information into climate models to more accurately represent what we could expect in the future."

The team's results were published in *Nature* (bit.ly/weakened-westerlies).

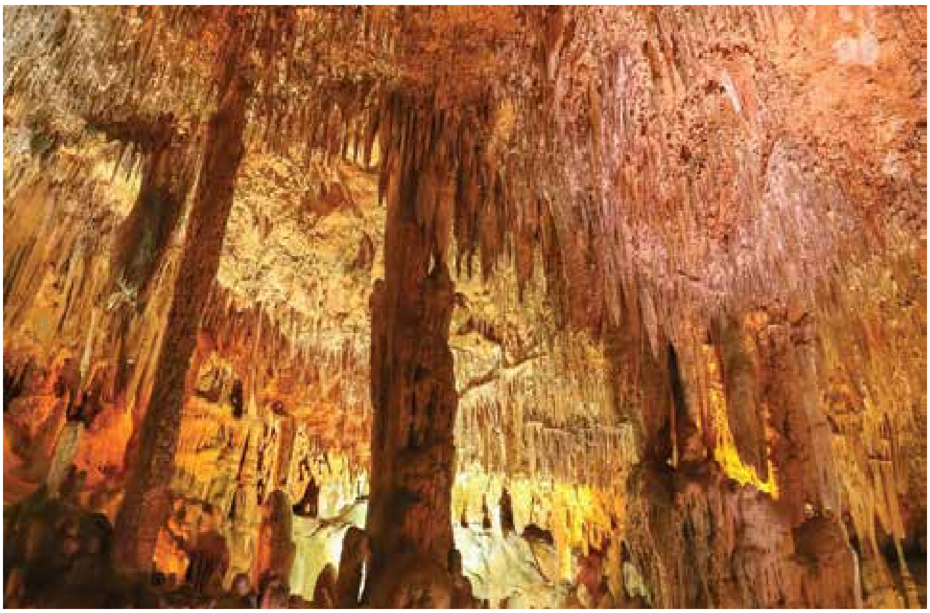
New Precipitation Patterns

The upshot of the phenomenon is that if Earth warms to the level of the Pliocene, the westerlies will no longer blow across the middle latitudes, which could mean much less rain for North America, Europe, and other temperate zones in the north, as well as in parts of Australia and New Zealand in the south. That shift may not happen for centuries, though, and there is still much to learn about how much of a shift will happen.

Abell and his coauthors hope to get more precise data about the degree of shift by studying sediment cores from when Earth was transitioning from the icy Pleistocene to the contemporary Holocene. There are many more sediment cores available for that time period than for the earlier Pliocene to Pleistocene, and by comparing a set of cores from north to south, the researchers believe they might be able to say how many degrees the westerlies will shift. "Our work in the Pliocene is really important," Abell said, "but being able to constrain some of these uncertainties even more is what we hope to do next."

By **Nancy Averett** (@nancyaverett), Science Writer

Sooty Layers in Stalagmites Record Human Activity in Caves



Researches are studying evidence of soot and charcoal from human-set fires in cave formations like these in Damlatas Cave in Antalya, Turkey. Credit: iStock.com/EvrenKalinbacak

Caves have long been used as places of shelter, burial, and ritual. Now researchers have analyzed stalagmites from two caves in southwestern Turkey and found that they contain layers of soot and charcoal, presumably from human-set fires. By precisely dating the stalagmite layers bracketing this black carbon, the scientists estimated that people were exploring these caves more than 6,000 years ago. These results reveal how geophysical data can complement archaeological records.

The Allure of Caves

To many ancient cultures, the dark passageways of caves represented a metaphorical connection to another world. Even today, with the advent of powerful flashlights that slice through darkness, caves are still alluring—the National Speleological Society, a nonprofit organization devoted to cave exploration, counts more than 7,000 members. "They're special places," said Koray Koç a paleoclimatologist at Akdeniz University in Antalya, Turkey.

In 2015, Koç and his colleagues headed underground to explore several caves in southwestern Turkey. Spelunking is always an adventure, said Koç, and these trips were no exception. In one cave, the team had to shimmy through an extremely narrow passageway barely wider than a person, and they found human and animal remains in addition to pieces of pottery.

"People might have used these caves as a shelter during the summer."

Natural Record Keepers

Koç and his collaborators observed many stalagmites and stalactites. Because speleothems like these grow slowly over time, they're record keepers of past environmental conditions: Scientists have used them to reconstruct droughts and climate variability, among other changes. Koç and his colleagues collected 16 stalagmites, the shortest about the length of a pinkie finger and the longest topping a meter.

Back in the laboratory, the scientists split the stalagmites lengthwise to reveal their interior layers. They were astonished to find that 14 of the stalagmites were shot through with layers of black soot and charcoal up to a millimeter thick and easily visible to the naked eye. That discovery changed the direction of the investigation, said Koç.

The researchers had initially planned to use the stalagmites to reconstruct the ancient climate in the region. "Our main purpose was to collect clean and suitable samples for paleoclimate research," said Koç. But now the hunt was on to better understand these layers.

Koç and his colleagues focused on three stalagmites from Tabak Cave and Kocain Cave with particularly well defined black layers. These layers, the researchers suggested, revealed a human presence in these caves.

Evidence of Fires

The black layers in the speleothems are the result of people carrying torches or setting fires in the caves, Koç and his collaborators said. Combustion releases particles of black charcoal that hitch a ride on air currents, and in a cave, some of these particles are bound to end up sticking to growing stalagmites. (The same effect can be seen today on the stone surfaces of old buildings exposed to pollution.)

The researchers estimated the ages of the speleothems' normal layers using uranium-thorium dating. By tabulating the ages of layers adjacent to each band of soot and charcoal, they estimated when the black carbon was deposited and therefore when humans were exploring these caves.

A Summer Refuge?

Koç and his colleagues found three layers of soot and charcoal in the stalagmites from Tabak Cave. They dated the layers to roughly 6,700, 7,100, and 7,400 years before the present, with an uncertainty of about 200 years. That's surprisingly early, said Koç, but it makes sense that people were inhabiting the caves. Turkey is notoriously hot in June, July, and August, so maybe these caves functioned as a refuge from the heat, he said. "People might have used these caves as a shelter during the summer."

It's unlikely that the layers of black carbon are due to nonanthropogenic triggers like faraway wildfires. That's because the ventila-

tion in Tabak Cave is poor—airborne particles circulating aboveground probably wouldn't have traveled far into the cave. (The stalagmites the researchers analyzed were tens of meters—and several narrow passageways—beyond the entrance.) Furthermore, archaeological artifacts like pottery shards found in Tabak Cave confirm the presence of humans deep underground who probably needed a source of light.

The stalagmite from Kocain Cave exhibited a wider spread in the ages of its five soot and charcoal layers: 470, 810, 1,500, 1,700, and 2,800 years before present. It's possible that some of these layers derive from aboveground fires, the researchers acknowledged, because of Kocain Cave's wide, open entrance and lack of narrow passageways.

These results are an important demonstration of the value of geophysical data, said Koç. The ability to precisely age date a speleothem has the potential to be a boon to archaeology, he said. "In archaeological studies, the trickiest part is getting robust ages."

"In archaeological studies, the trickiest part is getting robust ages."

Breaking Down Barriers

Ségolène Vandevelde, an archaeologist who studies speleothems at the University of Paris 1 Pantheon-Sorbonne, agreed. This work breaks down barriers between geological and archaeological approaches to science, said Vandevelde, who was not involved in the research. "Speleothems are often used as environmental and paleoclimate archives. Here, [scientists] use them as an archaeological record."

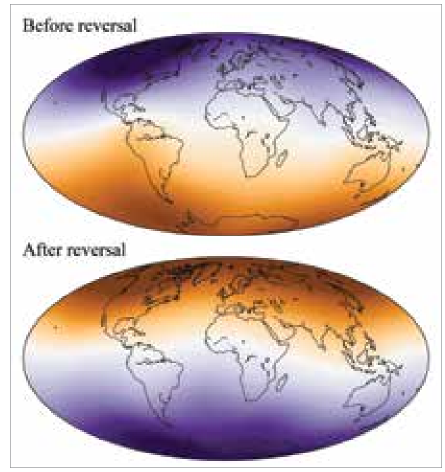
These results were published in the *Journal of Archaeological Science* (bit.ly/turkey-stalagmites).

A lot more information can be mined from these speleothems, said Vandevelde. "It'd be really interesting to synchronize all the different sequences of the Tabak Cave speleothems to reconstruct a complete chronology of human occupation in the cave."

By **Katherine Kornei** (@KatherineKornei), Science Writer

How Geodynamo Models Churn the Outer Core

Deep beneath our feet, Earth's liquid iron outer core sloshes and churns, slowly crystallizing to form the solid inner core while simultaneously generating our planet's magnetic field. In a recent study, Domenico Meduri, a geodynamo modeler at the University of Liverpool, focused on the past 10 million years of this erratic, roiling motion—more like river rapids than calm waters—using state-of-the-art computational facilities and refined code.



These maps show a simulated magnetic field reversal. Purple indicates a magnetic field pointing inward, toward the core, and orange indicates a magnetic field pointing outward and away from Earth's surface. The darker the shading, the more intense the magnetic field is. Credit: Domenico Meduri

Meduri and his team, using their own simulations, successfully reproduced salient features of the paleomagnetic field preserved in volcanic rocks. Such features include not only pole reversals—where north and south swap places—but also other fundamental characteristics of the paleomagnetic field recorded by rock samples.

Two ingredients spurred the team's success. They found that the most commonly modeled driver of the outer core's movements—differences in temperature—cannot explain paleomagnetic field measurements. Instead, it is the composition of the swirling liquid that plays an important role. Within the simulations, they also turned the knobs that approximate the physical characteristics of the moving molten metal, confirming that although Earth's core behaves mostly like a dipolar bar magnet—with only two poles—it may hover between the dipolar and multipolar regimes.

The research was published in *Geophysical Research Letters* (bit.ly/numerical-dynamo-simulations).

Stirring the Cauldron

Two phenomena drive the outer core's turbulent movement: thermal convection and compositional convection. Thermal convection occurs because the outer core is cooling along with the rest of Earth, explained Monika Korte, a paleomagnetist from the Helmholtz Centre in Potsdam, Germany, who was not involved in the new study. As the metallic liquid loses heat, colder material sinks toward the inner core, pushing hotter liquid upward, resulting in movement within the entire outer core driven by temperature variations, she said.

As the outer core processes form the inner core, said Korte, the light elements that crystallize at the boundary are too buoyant to be incorporated into Earth's metal heart and instead rise through the fluid, stirring the cauldron from the bottom up. This, she said, is compositional convection.

To model the two drivers of convection, Meduri said his team modified where the buoyancy forces congregate. "In the chemical model, [buoyancy forces] are located close to the inner core boundary, whereas in thermal models, [buoyancy forces are distributed] throughout the whole fluid."

None of Meduri's solutions driven by thermal convection matched the long-term paleomagnetic field data gleaned from rocks. The only ones that worked for his team, said Korte, were "those driven by compositional convection."

Bar Magnet Behavior

"To really have an Earth-like dynamo run—a long run that simulates thousands or millions of years of field evolution—[the run] should reflect the long-term average that we see in the data," said Korte. The simulation should include the observation that on average, the magnetic field tends to behave as though a bar magnet resides within Earth's core.

But a successful simulation must also capture reversals, which "are a fundamental feature of Earth's magnetic field," said Meduri. Other observations from paleomagnetic data,

like how variable the magnetic field intensity is and how much the geomagnetic poles wander, he said, must also be replicated.

Previous studies that could not successfully simulate paleomagnetic field data from the past 10 million years were "quite concerning," said Meduri. If simulations of Earth's geodynamo do not comply with paleomagnetic measurements, he said, "then what's the point of using these models to study the magnetic field?"

Changing the buoyancy force distribution—the major difference between compositional and thermal convection—will not, by itself, create Earth-like simulations, said Meduri. Instead, his team had to turn various knobs that change the physical properties of the modeled fluid.

These physical properties, said Korte, "are not exactly known because we cannot just go down to the Earth's core and directly measure them." Instead, she said, "they have to be inferred."

For example, one of these knobs controls the vigor of the liquid outer core's movement. Too calm? No reversals. Too turbulent? "The simulations are no longer very Earth-like," said Meduri, and behave not as a bar magnet but as multiple unstable poles protruding in different places—a multipolar magnetic field.

What you need, Meduri said, is to turn the knob just enough to find the "sweet spot" between those two magnetic regimes, where the geomagnetic poles flip every so often while maintaining that bar magnet-like behavior on average. For these successful simulations, the magnetic field briefly exhibits its multipolar behavior during the reversal before settling back down to look more like a stable bar magnet. "In this way," he said, "we could get dipolar [bar magnet-like] models with high-enough directional and intensity variability."

"That's really the fundamental contribution of our work," Meduri said. "We've known for at least 25 years that numerical simulations capture reversals, but do they also capture the directional and intensity variability we observe [in the rocks] on these long timescales or not?"

"Our work," he said, "is really a bridge between purely theoretical dynamo simulations and what we observe of the Earth's magnetic field. We were trying to match the two."

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

Finding "Glocal" Solutions to Flooding Problems

Xin'an River Hydropower Station, in the province of Zhejiang, China, discharges floodwaters of Qiandao Lake in July 2020, a period of record rainfall in the region. Credit: MasaneMiyaPA/Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Type "flooding today" into your search engine and you will likely find at least one place battling rising waters somewhere in the world—Mozambique today, Yorkshire yesterday, Hawaii tomorrow. Floods occur when water encroaches on dry land, which can happen during hurricane-induced storm surges or when heavy precipitation (or snowmelt) has nowhere to go. These different flood sources have an important commonality: They all start with weather.

"Weather patterns, which cause flooding, are happening at the global scale," said Guy Schumann, a flood hydrologist with the University of Colorado Boulder's Institute of Arctic and Alpine Research, "but impacts of floods are very localized." Local effects include costs to the economy, displacement of populations, and loss of life.

Schumann and a team of scientists led by Huan Wu, a professor at Sun Yat-sen University in Guangdong, China, developed an innovative flood model linking global precipitation patterns with localized hydrology—where water goes once it finds land. Their work, published in *Advances in Atmospheric Science*, provided useful information to the Chinese Ministry for Emergency Management when record rainfall in 2020 posed an immediate threat—an event that eventually affected 40 million people, according to Wu's team (bit.ly/glocal-solution).

Forecasting Floods Throughout the World

Global flood models approximate the complex relationships between precipitation and local hydrology. Accurate, real-time precipitation data buttress any such model.

Some global flood models use satellite-measured precipitation estimates, but according to Bob Adler, an atmospheric scientist at the University of Maryland not involved with Wu's latest work, "it's a very complex thing trying to estimate surface rainfall—what's falling out of the bottom of a cloud—by looking at it from space." One upgrade in Wu's calculations, Adler said, is the use of numerous rain gauges China has installed. These gauges can feed accurate, real-time precipitation data into the model to produce high-quality rain forecasts. Such forecasting, said Wu in his paper, "always plays the most important role in driving models."

If precipitation data and forecasting provide the foundation, hydrology frames the rest of the issue with regional- and local-scale runoff and routing models that follow rain when it hits land. The hydrology component begins with a land surface model that dictates how much water goes into the ground versus how much is available as runoff, said Adler. Then the runoff goes into a routing model that directs the water downstream, he said, allowing scientists to calculate the total volume of water flowing through a river at a given time.

With this information, Wu and his colleagues can forecast areas likely to be inundated with water—information best visualized as a flood map. Providing these "timely and accurate maps showing current and days-ahead flood risk [is the responsibility of] the international hydrometeorological community," said Wu and his coauthors in their paper.

As an end user of flood maps, natural hazard mitigation strategist Kevin Zerbe, not part of this study, said that inundation at the spatial resolution Wu provided to the Chinese gov-

ernment—water depth every 5–10 meters—is "what's really missing." At least in parts of China, Wu found a way to model the hydrology of each watershed that, Zerbe said, is so unique and continually changing. According to Zerbe, "those kinds of mapping products would be valuable when it comes to preparing for an oncoming flooding event."

The Valley of Death

Wu and his team bridged what Schumann called the "valley of death," or the gap between scientists and end users. By connecting to the national authorities in China, Schumann said, "[Wu] managed to get his model into the hands of the...people who are responsible for acting."

The metaphorical valley of death can become literal when scientists cannot communicate with decisionmakers, especially in countries that may not be able to make their own flood maps. Global flood models serve a humanitarian purpose, said Schumann, letting agencies like the United Nations rapidly respond to flooding in regions with fewer resources. In particular, Wu and his colleagues called on meteorologists and hydrologists to work together on "glocal" solutions, reflecting the dual nature of the problem.

"We [need] a lot more local information in these global models," Schumann said, which, he explained, must include a global high-resolution topographic data set to underlie runoff models and maps of existing local flood defenses—levees, walls, and dams, for example—that control where water flows. The best freely available global digital elevation models of topography have a resolution of 30 meters per pixel, he said, and they're often outdated because topography changes in regions with active tectonics or flooding. To obtain higher-resolution data, he said, "someone needs to pay for that."

The need for global models that can accurately forecast flooding several days ahead while providing information at both local and regional scales has never been higher. As the climate warms and exacerbates extreme precipitation events, Zerbe said, flooding events will become more unpredictable. "Climate change is invalidating history as a good indicator of what's going to happen in the future, and that's all the more reason that we need really great modeling and simulations and data," said Zerbe. "History just isn't as reliable as it once was."

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

More Acidic Water Might Supercharge Lightning

A simple laboratory experiment has sparked new insight into the potential impact of climate change on the intensity of ocean lightning. A team of researchers in Israel gradually changed the acidity of a beaker of water while shooting it with an electrical spark. As the water became more acidic, the flash became brighter. If what they observed in the lab is indicative of how lightning acts in nature, ocean lightning could become around 30% more intense by century's end under a worst-case climate scenario, according to the scientists.

Such a rise in intensity could threaten the safety of marine life and oceangoing vessels alike, the authors of a paper in *Scientific Reports* argue (bit.ly/lightning-intensity). But other experts in the field caution that this makeshift lightning in a beaker could behave very differently than real-world lightning in the atmosphere.

An Illuminating Line of Inquiry

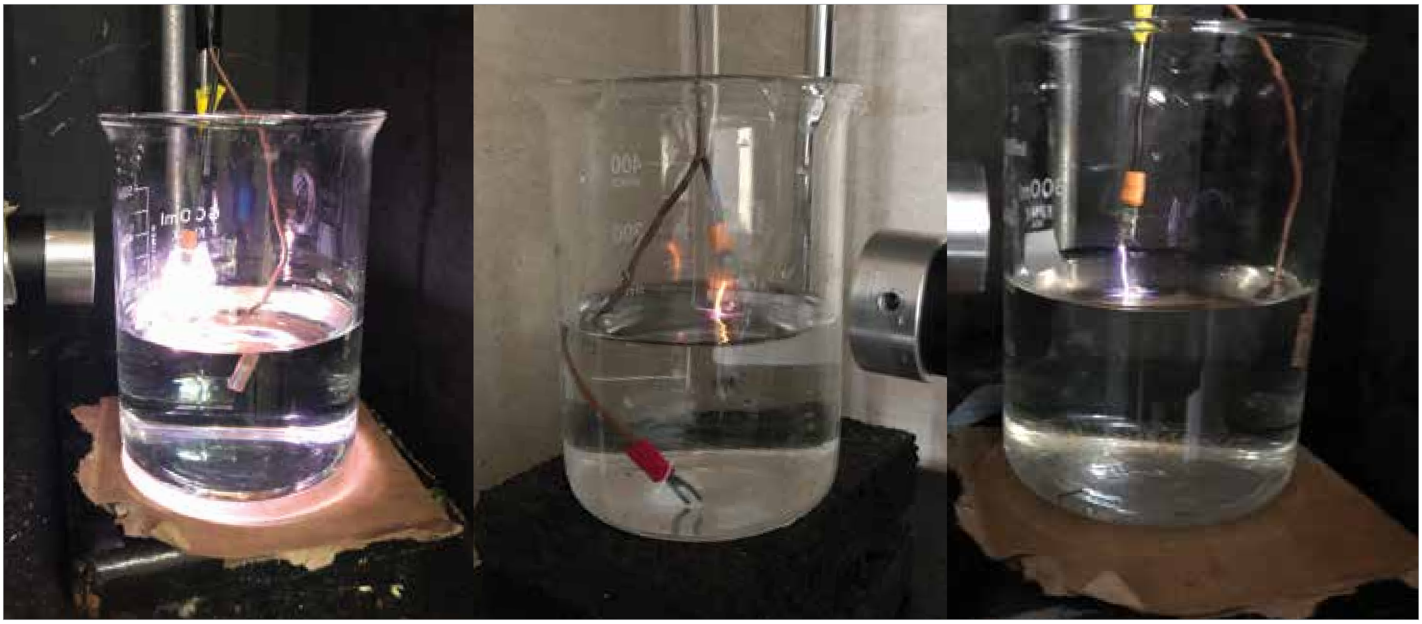
The idea for the experiment started with a conversation over lunch between lead author Mustafa Asfur, a lecturer at Israel's Ruppin Academic Center, and Jacob Silverman, an ocean biogeochemist with the National Institute of Oceanography in Haifa. "I started to ask innocent questions about what happens to seawater when lightning strikes it," Silverman said.

When Asfur and Silverman began digging into the scientific literature, they were met with a surprising answer: Nobody knows. The prevailing assumption in the field was that any surface on Earth—rock, soil, ocean, or lake—could be considered a perfect conductor. But data show that lightning behaves differently over land than over sea—it is far more frequent over continents, and evidence suggests that it is often more intense over the ocean.

The researchers wondered whether the ocean itself could have something to do with the pattern.

A 2019 paper in the *Journal of Geophysical Research: Atmospheres* mapped the global distribution of a kind of lightning known as a superbolt, which is 100–1,000 times brighter than an ordinary lightning bolt (bit.ly/superbolts). Researchers found that almost all superbolt hot spots were over oceans and seas, but they had no ready explanation for why that might be the case.

Silverman and Asfur wondered whether the ocean itself could have something to do with the pattern. "I have a feeling that maybe we're



In a new experiment, researchers filled beakers with water and suspended one electrode about a centimeter above the water and another about 3 centimeters below, in a setup that produced a 1-million-volt spark with a current of about 20 amperes. When pure water (center) was made saltier (left) or more acidic (right), the spark became visibly brighter. Credit: Mustafa Asfur

missing something," Silverman said. "Maybe the conductivity of the ground does matter."

A Strikingly Simple Setup

To test the idea, Asfur and his team came up with a simple laboratory setup that replicated lightning striking the ocean. They filled a beaker with water and suspended one electrode about a centimeter above the water and another about 3 centimeters below, in a setup that produced a 1-million-volt spark with a current of about 20 amperes. They measured the spark's intensity using an optical fiber spectrometer that measured relative irradiance units.

The team first measured how salinity affected the brightness of the spark, zapping water ranging from normal tap water to a salty sample from the Dead Sea. Sure enough, the sparks in the saltier beakers produced brighter flashes, the team reported in a study published last year (bit.ly/intense-lightning-over-oceans).

Next, the researchers turned their attention to another property of water that can change its conductivity: acidification. They used two methods of changing the pH of the water in the experiment by adding a strong acid and by bubbling carbon dioxide. Like salinity, acidification had a measurable impact on the brightness of the sparks. The spark intensity increased more than 2 times faster using the carbon dioxide bubbling method to lower the pH.

"A simple experiment goes a long way toward provoking ideas and provoking further work."

These results "caught me off guard at first," said Earle Williams, a physical meteorologist with the Massachusetts Institute of Technology who was not involved in the study. "My expectation was that it wouldn't matter much what the material was."

More Than Just a Flash in the Beaker?

If lightning is indeed growing more intense over the oceans as climate change makes oceans more acidic, shipping vessels, oil rigs, and other ocean infrastructure might need to update their lightning protections. More intense lightning over the oceans could also produce louder booms that stress sea creatures already harried by human noise pollution.

But it's not time to start implementing new lightning protections just yet, according to Vernon Cooray, a lightning physicist with Uppsala University in Sweden who was not involved in the study. Cooray said that a spark of a few centimeters interacts with water very differently than a spark of several hundred meters.

"The methods are sound, and the conclusions made about the laboratory discharges are correct," he said. "Unfortunately, the results cannot be extended to lightning."

Williams also advised caution about applying the lab results to real-world lightning, which is not only much longer but also at least 100 times more intense. Even so, he considers the new research to be valuable.

"It's an important contribution whenever you have results in the lab where you can measure things that shed important light on large-scale phenomena," he said. "A simple experiment goes a long way toward provoking ideas and provoking further work."

By **Rachel Fritts** (@rachel_fritts), Science Writer

Drought, Not War, Felled Some Ancient Asian Civilizations

The central Asian civilizations of the Otrār oasis, located at the junction of the Syr Darya and Arys Rivers in what is now southern Kazakhstan, flourished during classical antiquity.

Located on the Silk Road, with access to floodwater-irrigated land spanning some 50,000 square kilometers (about twice the size of Mesopotamia), the region became known as Transoxania. At its height, it was described as the "land of the thousand cities."

However, the region fell into stagnation at the end of the Medieval period, with its decline coinciding with a Mongol invasion in the early 13th century. After a partial recovery, Otrār finally collapsed by the 17th century and the region remains uninhabited today.

But the cause of Otrār's decline was likely not the changing tides of warfare but instead the changing climate.

Mongol warriors like these have long been associated with the fall of the central Asian civilizations of Transoxania, but climate change may have been as much to blame. Credit: From the Jāmiʿ al-tawārīkh

The Sands of Time

In a new study published in the *Proceedings of the National Academy of Sciences of the United States of America*, an interdisciplinary team of researchers reported that the Otrār oasis had been in a prolonged period of decline long before the Mongols invaded (bit.ly/central-asia-river-civilizations).

The clues lie in irrigation canals that the ancient civilizations of Transoxania relied on for agriculture.

"People and communities lived and were shaped by the environment," said Mark Macklin, a professor of river systems and global change at the University of Lincoln in the United Kingdom. "And in the case of central Asia, [they] may be shaped by the availability of water.... If you don't have water, you don't have crops; you can't live."

Transoxania's canals were previously thought to have been destroyed by the Mongols during their invasion. Macklin and his colleagues studied the canals with a combination of radiocarbon dating and a technique called optically stimulated luminescence (OSL), which dates the last time that sand was exposed to sunlight.

"We assumed with our dating that the canals would have been abandoned only when the Mongols arrived," Macklin said. "But that wasn't the case. They were already going into disuse probably 100 years before."

The researchers collected samples from the canals by hammering metal scaffolding tubes into the sediment, being careful to seal both ends from light exposure before they were shipped back to the laboratory for analysis.

"We assumed with our dating that the canals would have been abandoned only when the Mongols arrived. But that wasn't the case. They were already going into disuse probably 100 years before."

"Every handful of sand is radioactive," said Tammy Rittenour, a professor of paleoclimatology and Quaternary geology at Utah State University whose lab specializes in the OSL technique but who was not involved in this study. When the sand is exposed to the Sun, its luminescence signal is known and effectively "zeroed." And when the sand is buried—because, say, the canal that was carrying the sand was no longer flowing—it is exposed to the latent radioactivity of the surrounding sediments.

"There's basically a proportionality between radiation exposure and luminescence," and with knowledge of the rate of radiation exposure, it is possible to calculate when the sand was buried, said Rittenour.

The researchers also reconstructed climate records in the region over the past 2,000 years, which revealed that the canals were abandoned during periods of prolonged drought that both weakened the civilizations before the Mongols arrived and stunted their recovery afterward. Archaeological records further corroborated the coincident timing of the region's cultural decline.

Climatic and Cultural Interactions

Climate conditions likely interacted with regional conflict to influence the rise of Trans-

oxania as well as its fall. For example, an Arab invasion between 650 and 760 coincided with a wet period, and the region not only recovered quickly but prospered afterward, Macklin said. "By contrast, when the Mongol army arrived in 1218, there [had been] probably 100–150 years of prolonged drought, and already the place wasn't in good shape."

These converging lines of climatic and cultural interactions paint a more nuanced picture of human history in the region, one in which the climate helped shape the legacies of militaristic ambitions.

"History never, ever quite repeats itself. Our understanding of what happened in the past is informative of what we can say might happen in the future."

One take-home message of the study is the power of applying multiple dating methods "to ensure you know the age of your features or your deposits, so you can really confirm the results," said Rittenour. "And that, along with the link to archaeology, cultural changes, and climate, makes this an excellent paper."

"History never, ever quite repeats itself," Macklin said. "Our understanding of what happened in the past is informative of what we can say might happen in the future."

Indeed, central Asia looks very different today, with large-scale commercial farming dominating the landscape. The Aral Sea, into which the life-giving rivers of Transoxania drain, has now virtually disappeared, Macklin said.

"This research is showing that climate change does have a real impact on society," he said. "And we can see that very clearly. It can happen very rapidly. You can see it within a generation."

And, he added, "the rate of climate change [in this study] is significantly less than what we're seeing now."

By **Richard J. Sima** (@richardsima), Science Writer

An Asteroid "Double Disaster" Struck Germany in the Miocene

St. George's church in Nördlingen, Germany, is built from rock forged by an asteroid impact. Credit: Renardo la vulpo/Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-02)

A Gothic church rises high above the medieval town of Nördlingen, Germany. But unlike most churches, St. George's is composed of a very special type of rock: suevite, a coarse-grained breccia that's formed only in powerful impacts. That discovery and other lines of evidence have helped researchers determine that Nördlingen lies within an impact crater. Now scientists have unearthed evidence that this crater and another one just 40 kilometers away were formed by a "double disaster" of two independent asteroid impacts. That revises a previous theory that these features are the relics of a one-two cosmic punch from a pair of gravitationally bound asteroids striking Earth simultaneously.

A Handful of Double Craters

Our planet is dotted with nearly 200 confirmed impact structures, and a handful of them appear in close pairs. Some researchers have proposed that these apparent double craters are scars created by binary asteroids slamming into Earth at the same time. That makes sense, said William Bottke, a planetary scientist at the Southwest Research Institute in Boulder, Colo., not involved in the new research. "We don't have that many craters on the Earth. When you see two sitting right next to one another, it's natural to think there's an association."

However, scientists have theoretically determined that the binary asteroid scenario is unlikely. That's because most binary asteroids orbit each other too closely to produce two distinct craters were they to slam into a rocky body, Bottke and his colleagues showed back in the 1990s. "If you're going to get two separate craters from the impact of a binary asteroid, they have to be pretty well separated," said Bottke.

Two Craters near Stuttgart

Now Elmar Buchner, a geologist at the Neu-Ulm University of Applied Sciences in Germany, and his colleagues have investigated the provenance of two impact craters near Stuttgart using observational data. They focused on the 24-kilometer-diameter Ries crater—which encompasses the town of Nördlingen—and the 4-kilometer-diameter Steinheim Basin, which are located roughly 40 kilometers from each other.

The Ries crater formed about 14.8 million years ago during the Miocene epoch, Argon-argon age dating has revealed. The age of the Steinheim Basin hasn't been conclusively

measured, but some researchers have suggested that it formed contemporaneously. "It was nearly dogma in Germany that this must be the result of a double impact at the same time," said Buchner.

Two Episodes of Ground Shaking

Buchner and his collaborators investigated outcroppings of rock in the region around the craters and found a layer of jumbled, fractured sediments. That wasn't a surprise—such seismites are a sign that powerful seismic waves passed through the region, which would have certainly occurred after an asteroid impact. However, the researchers found that this seismite horizon was crosscut by a second horizon, this one consisting of vertical tubelike features known as clastic dikes. The discovery of these two distinct seismite units is evidence of two separate episodes of ground shaking, Buchner and his colleagues concluded. That rules out a strike by a binary asteroid, which would have launched just one round of seismic waves.

The researchers found that this seismite horizon was crosscut by a second horizon, this one consisting of vertical tubelike features known as clastic dikes.

The impact that created the Ries crater must have formed first, the scientists surmised, because blocks of limestone—ejecta from the Ries impact—cap the lower seismite horizon. That's consistent with previous research suggesting that fossils within the Ries crater are a few hundred thousand years older than fossils found within the Steinheim Basin.

This region "witnessed a double disaster in the Middle Miocene," the researchers concluded in their paper, which was published in *Scientific Reports* (bit.ly/seismite-horizons). That's rare but not unheard of, said Bottke. "If you only have so much terrain and you keep adding craters, eventually, two are going to be very close to one another, just by chance."

By **Katherine Kornei** (@KatherineKornei), Science Writer

Trees That Live Fast, Die Young, and Mess with Climate Models

Under a business-as-usual scenario of greenhouse gas emissions, the average global temperature might increase by almost 5°C through the end of the century. This climate change could cause a 1-meter increase in sea levels, possibly wreaking havoc on coastal regions and demanding hundreds of billions of dollars every year in adaptation and mitigation measures. As grim as this scenario may sound, it might be optimistic.

According to recent research, there are carbon cycle feedbacks not accounted for by current climate models. The reason is that forests, which can absorb about a third of greenhouse gas emissions, might be relatively short-lived carbon stocks in the future as trees live fast and die young.

Scientists are concerned because carbon uptake is a "critical ecosystem service that our forests are providing by effectively slowing the rate of climate change—and buying us time while we figure out policies to address it," said Andrew Reinmann, an assistant professor of geography at the City University of New York.

Carbon dioxide (CO_2) stimulates the growth of trees due to carbon uptake during their development. This process, which scientists call CO_2 fertilization, can accelerate tree growth, with more carbon available in the atmosphere (especially under higher temperatures) causing trees to have shorter life spans. The trees die sooner because higher metabolism rates can cause them to age faster and invest less in defenses or a more efficient hydraulic architecture, or simply cause them to reach their maximum size sooner in life. The entire process means that trees will store carbon for a shorter time, accelerating the carbon cycle and potentially increasing carbon concentrations in the atmosphere.

Forests in temperate and boreal regions, like this one at Parc Régional du Poisson Blanc in Quebec, Canada, store much of their carbon in the soil, as organic matter takes longer to decompose and, consequently, release CO_2. Credit: Ali Kazal/Unsplash

"This can have an important effect on forest carbon sinks in the future," said Roel Brienen, a professor at the School of Geography at the University of Leeds in the United Kingdom.

Brienen led a study showing that the trade-off between tree longevity and growth rate is almost universal, extending from high latitudes to the tropics. An international team of researchers observed tree ring data sets on 110 tree species all over the world and noticed that on average, 50% of early growth increase meant a 23% life span reduction. "While this relation across species was already known, we found this difference also occurs within species," Brienen said.

The finding is important, but the paper doesn't account for the variation in tree reproduction and seedling production, observed Oswald Schmitz, a professor of population and community ecology at Yale University's School of the Environment not involved in the study.

It's possible that there could be a carbon balance, with enough sprouting seedlings to replace dead trees, said Schmitz—but the carbon cycle is rarely that simple. "Carbon cycle models don't really account for such nuanced dynamics, especially if there's regeneration failure—by continuing deforestation, for instance," Schmitz explained.

Temperature might play an important role in the relationship between tree longevity and growth as well: According to another paper from the same group, published in the *Proceedings of the National Academy of Sciences of the United States of America*, tropical trees grow twice as fast as those in temperate and boreal regions but live half as long (bit.ly/tropical-tree-longevity). The study analyzed tree ring data from more than 3,300 tree populations and 438 species across different biomes.

Lead author Giuliano Locosselli, a researcher at the Biosciences Institute at the University of São Paulo in Brazil, said there is only so much heat trees can withstand without having their life spans shortened. The hotter it gets, the more water evaporates from trees. "We saw that mean annual tem-

peratures above 25.4°C affect tree longevity because [trees are] already operating in their limit—too much evaporation might cause water stress and affect their survival," Locosselli said.

Climate Modeling Challenges

According to Reinmann, merging these and other processes that happen to trees into global carbon cycle–climate feedback models would make them a lot more accurate than they are now. Overall impacts could be immense. "If, under a future climate, forest carbon absorption plummets and we didn't account for that, we would throw off the effectiveness of our climate change policies," he said.

Incorporating and verifying such diverse data, however, is a Herculean task. Pieter Tans, a senior scientist at NOAA's Global Monitoring Laboratory not involved in the research, pointed out that in addition to data about forest carbon, assessing a forest's effect on climate models must also include soil moisture conditions and carbon storage, aboveground plant canopy structure, and myriad other variables.

A particularly difficult assessment to make involves the gas itself. "It's easier for us to see something in methane than in CO_2," Tans said. "Carbon dioxide has large sources and large sinks, with huge fluxes of net photosynthesis and seasonal uptake, for example—but the respiration that returns that gas to the atmosphere is equally large, and there's also a large interannual variability."

The research community is rising to the challenge. Brienen has been working with a group in France to incorporate tree longevity trade-off data in the Organising Carbon and Hydrology in Dynamic Ecosystems land surface model. "It only started quite recently, so we don't have any results to show yet," Brienen said.

As more accurate climate models are still in the works, researchers were unanimous about one thing: We have to do more as a society to curb greenhouse gas emissions to avoid further strangling natural carbon uptake capacities.

"We know what to do," Tans said. "We can still have a good life while consuming a lot less energy. Renewables technology is ready to go. Furthermore, if we think about the work it'll take to reform our entire energy infrastructure, it's really a jobs program."

By **Meghie Rodrigues** (@meghier), Science Writer

Tree Rings Reveal How Ancient Forests Were Managed

Clear-cutting a forest is relatively easy—just pick a tree and start chopping. But there are benefits to more sophisticated forest management. One technique—which involves repeatedly harvesting smaller trees every 30 or so years but leaving an upper story of larger trees for longer periods (60, 90, or 120 years)—ensures a steady supply of both firewood and construction timber.

To determine when this management practice first arose in Europe, researchers have analyzed oak construction timbers from historical buildings and archaeological sites dating from the 4th to the 21st century. They spotted a characteristic tree ring pattern indicative of this technique in timber dating back to the 6th century. That was a surprise, the researchers noted, because this forest management practice shows up in historical documents beginning only in the 13th century.

A Pattern in the Rings

The coppice-with-standards management practice produces a two-story forest, said Bernhard Muigg, a dendrochronologist at the University of Freiburg in Germany. "You have an upper story of single trees that are allowed to grow for several understory generations."

That arrangement imprints a characteristic tree ring pattern in a forest's upper story trees (the "standards"): thick rings indicative of heavy growth, which show up at regular intervals as the surrounding smaller trees are cut down. "The trees are growing faster," said Muigg. "You can really see it with your naked eye."

Muigg and his collaborators characterized that dendrochronological pattern in 161 oak trees growing in central Germany, one of the few remaining sites in Europe with actively managed coppice-with-standards forests. They found up to nine cycles of heavy growth in the trees, the oldest of which was planted in 1761. The researchers then turned to a historical data set—over 2,000 oak timbers from buildings and archaeological sites in Germany and France dating from between 300 and 2015—to look for a similar pattern.

A Gap of 500 Years

The team found wood with the characteristic coppice-with-standards tree ring pattern dating to as early as the 6th century. Muigg and his colleagues were surprised by this, because no mention of this forest management practice appears in historical documents until roughly 500 years later, in the 13th century.

It's probable that forest management practices were not well documented prior to the High Middle Ages (1000–1250), the researchers suggested. "Forests are mainly mentioned in the context of royal hunting interests or donations," said Muigg. Dendrochronological studies are particularly important because they can reveal information not captured by a sparse historical record, he added.

These results were published in *Scientific Reports* (bit.ly/sustainable-forest-management).

"It's nice to see the longevity and the history of coppice-with-standards," said Ian Short, a forestry researcher at Teagasc, the Agriculture and Food Development Authority in Ireland, not involved in the research. This technique is valuable because it promotes conservation and habitat biodiversity, Short said. "In the next 10 or 20 years, I think we'll see more coppice-with-standards coming back into production."

In the future, Muigg and his collaborators hope to analyze a larger sample of historic timbers to trace how the practice spread throughout Europe. It will be interesting to understand where the technique originated and how it propagated, said Muigg, and there are plenty of old pieces of wood waiting to be analyzed. "There [are] tons of dendrochronological data."

By **Katherine Kornei** (@KatherineKornei), Science Writer

The Influence of Tidal Forces Extends to the Arctic's Deep Sea

From more than 384,000 kilometers away, the Moon's gravity pulls at Earth and its oceans, affecting activity even hundreds of meters below the sea surface. Oceanographers know that tides can affect methane emissions that seep from the seafloor, and now a research team has shown that this influence extends into the deep Arctic.

Unexpected Findings

The team, led by Nabil Sultan, a geotechnics researcher at the French marine sciences institute Ifremer, set out to the Arctic Ocean. The team intended to measure the pressure and temperature of fluids within the sediments along the Vestnesa Ridge on the Svalbard continental margin to see how geological processes in the area might affect that pressure. The researchers chose two sites that they expected wouldn't have methane gas plumes, trying to avoid geologically active structures to learn about background sediment properties.

To get their measurements, the team deployed a piezometer, a rodlike device that can measure pressure within sediment pores, equipped with temperature sensors. Embedded 7 meters into the sediment of the Arctic seabed, the device collected data for 4 days before the researchers brought it back to the surface. They collected pore pressure and temperature measurements at two sites, one at 910 meters deep and another at 1,330 meters.

When the researchers got their data, their first surprise was that the pressure readings suggested the presence of methane seeps. "We were not expecting to see any gas in the area," said Sultan.

Previous hydroacoustic surveys, the traditional method used to detect these seeps from the local seabed, hadn't shown the presence of free gas. Because surveys can't continuously monitor the seafloor, they can miss signs of emissions that a piezometer stuck in the sand for days can pick up. "With this monitoring method, we were able to show that the extension of the area where we have degassing is much [larger] than what we're observing with classical methods," said Sultan.

The team's next surprise was that the amount of methane released from the sediment seems to fluctuate throughout the day. "Why can we see so much change within 3 days?" wondered Andreia Plaza-Faverola, a project leader at Norway's Centre for Arctic Gas Hydrate, Environment and Climate, and a coauthor of the study. "There are not many things that could explain those peaks in the pressure."

The team compared its data with the tidal cycles and found an answer. The pore pressure hundreds of meters below the ocean surface seemed to change with the tides, even though tidal height varied by just 1 meter. Through modeling, the group also saw that at low tide, when water column height decreased by about 1 meter, the pressure in the water column dropped, which the authors think allowed gas seepage through seabed fractures, whereas high tides seemed to reduce both the height and the volume of methane emitted.

"It is interesting to see with this data that such small changes in pressure are affecting gas accumulations that are very close to the seafloor," said Plaza-Faverola.

The pore pressure hundreds of meters below the ocean surface seemed to change with the tides, even though tidal height varied by just 1 meter.

However, the scientists had only pressure and temperature measurements and weren't able to observe gas bubbles at the sites. In future studies, the group is hoping to use remotely operated vehicles to observe bubbles and see whether their release aligns with the cycles identified in this study. The findings are also limited to two sites and data recorded over a few days, and the team hopes to collect data at more locations at longer timescales to see how generalizable the present findings might be.

Sensitive and Elusive Seeps

One of the most notable consequences of the research, published in *Nature Communications* (bit.ly/arctic-methane-emissions), is that it shows there could be much more gas activity than scientists are picking up with hydroacoustic surveys, the traditional method for identifying methane emission sites. "They're able to address what's happening between acoustic surveys, and what's happening is a really cool high-frequency change in methane flux," said Joel Johnson, a geology professor at the University of New Hampshire. "There might be more gas going into the ocean than we thought because of this tidal flux above faulted areas where there's lots of free gas."

This study also highlighted the sensitivity of gas systems hundreds of meters below the surface. The findings suggested that a sea level rise of even 1 meter would be enough to affect the release of methane hundreds of meters below. At these depths, the methane dissolves in water before reaching the surface. In shallower areas (less than 50 meters deep), however, methane can reach the atmosphere. Future sea level rise could offset some of those emissions.

"We're not saying that the increase in water height is a good thing," said Sultan. But the pressure changes that will come with rising waters merit more investigation. "We need to consider how pressure will impact this gas system.... It's urgent today to go study in more detail the shallowest areas in the Arctic or in areas where you have high concentrations of gas and gas hydrates."

Aboard the R/V Kronprins Haakon, *scientists deployed piezometers to measure sediment properties. Credit: Robin Hjertenes*

By **Jackie Rocheleau** (@JackieRocheleau), Science Writer

Opposite: iStock.com/Ja'Crispy

This Search for Alien Life Starts with Destroying Bacteria on Earth

Sometimes it takes a little destruction to unlock the secrets of the universe.

In a lab at Imperial College London, Tara Salter used high temperatures to destroy samples of bacteria and archaea, leaving behind molecular fragments. With this pyrolysis process, Salter attempted to simulate what might happen to molecules that smash into a spacecraft like bugs on a windshield.

Specifically, Salter simulated a spacecraft flying through the geyser-like plumes of the outer solar system's ocean moons. Scientists have observed plumes spouting from the icy shells of both Saturn's moon Enceladus and Jupiter's moon Europa—and they want to send spacecraft through those plumes to investigate what kinds of molecules are being ejected from the extraterrestrial oceans below.

Any molecule colliding with a spacecraft flying at speeds of several kilometers per second would be "smashed to smithereens," Salter said.

Even if microbes are part of plume ejecta, sampling spacecraft likely won't be able to observe entire organisms—just bits of them. "Being able to put back together the organism from detecting small parts is the big aim" of her research, Salter said. She hopes that her smashed-up bacteria samples, and the molecular fragments they leave behind, will help future scientists investigate the possibility of life on one of these ocean worlds.

Salter presented the research at AGU's Fall Meeting 2020 (bit.ly/life-on-icy-moons).

"Being able to put back together the organism from detecting small parts is the big aim."

NASA's Europa Clipper, set to launch in 2024, will study Jupiter's icy moon Europa. Credit: JoAnna Wendel

Far-Away Oceans

Back in 2005, NASA's Cassini spacecraft made a spectacular discovery: Underneath many kilometers of ice on Saturn's moon Enceladus churned a vast ocean of liquid water. Cassini discovered this ocean almost by accident when it flew through geyser-like plumes of water vapor spewing from Enceladus's south pole. Cassini didn't discover just water molecules in the plume—there also seemed to be fragments of organic molecules clinging to the speeding grains of ice.

But Cassini's instruments weren't designed to distinguish between large organic molecules, said Hunter Waite, a program director of mass spectrometry at the Southwest Research Institute in San Antonio.

Now that we know that a future spacecraft needs to be able to detect large, complex organics, NASA is prepared. The agency's next mission to the outer solar system, Europa Clipper, will study another moon that contains a liquid water ocean, Jupiter's satellite Europa. Numerous observations from the Galileo spacecraft and the Hubble Space Telescope indicate that like Enceladus, Europa sports plumes shooting from its surface. Whether those plumes originate in the moon's internal ocean or in a subsurface reservoir remains to be seen.

Europa Clipper's mass spectrometer will be able to detect and determine the composition of larger organic molecules, said Waite, who is also a coinvestigator on the instrument. That way, scientists will be able to study exactly what material is coming out of the plumes.

Flying Through Plumes...in the Lab

To simulate a spacecraft's flight through Europa's plumes, Salter heated specimens of extremophile bacteria in a special chamber to 650°C, which mimics the destructive force of smashing into a spacecraft. The heat destroys the molecules to some extent, and what's left is a smorgasbord of fragments. Salter then analyzed fragments with her lab's mass spectrometer and created a catalog.

"You can simplify a bacteria into proteins, carbohydrates, and lipids," among other things, Salter said. In her analysis, she found fragments of amino acids; fatty acid chains that make up lipids; and molecules containing oxygen, hydrogen, and carbon from the carbohydrates.

After analyzing the fragments, Salter created a library of molecular signatures—one she hopes to expand and share with fellow scientists.

"Work like this can help us unlock hidden gems in previous data sets like the measurements Cassini made of the Enceladus plume and will also help us inform future measurements by missions designed to search for life in these alien oceans," said Morgan Cable, a planetary scientist at NASA's Jet Propulsion Laboratory in Pasadena, Calif., who wasn't involved in the research.

However, "we also need to keep in mind that we might encounter only trace amounts of life, where that biosignature spectrum could be hidden underneath a strong abiotic signature," she said.

Salter has more plans for destruction. She wants to destroy bacteria cells using ultraviolet radiation—to mimic the surface of Europa—and to heat up the cells in the presence of water to see how water affects what molecules get left behind.

From the dust of pulverized bacteria, scientists hope to compile a complete library of molecular fragments that can help identify life on another world.

By **JoAnna Wendel** (@JoAnnaScience), Science Writer

Terrestrial Plants Flourished After the Cretaceous–Paleogene Extinction

At first glance, Chambery Coulee might look like any other valley in the vast prairies of southern Saskatchewan. But for Robert Bourque and his colleagues at McGill University in Quebec, Chambery Coulee is a window into the deep past, a place that holds the secrets of the mass extinction that ended the age of the dinosaurs 66 million years ago.

Their recent study uses compounds in plant waxes to shed new light on how plant communities, the water cycle, and the carbon cycle changed after the dinosaur-killing Chicxulub asteroid impact, which marked the end of the Cretaceous period and the beginning of the Paleogene (bit.ly/terrestrial-ecosystems). Bourque, who received his master of science degree from McGill and is now a Ph.D. student at Rensselaer Polytechnic Institute in New York, said, "Plant waxes provide a unique opportunity in looking through certain lenses at the global ecosystem at the time, since plant waxes record atmospheric [carbon dioxide] as well as the hydrogen derived from rainfall. So we're able to use them as proxies for looking at these environmental signatures."

Even though it is now widely accepted that the asteroid impact was the root cause of the extinction event, the specific mechanism (or mechanisms) by which the impact wiped out the majority of all plant and animal species on Earth is still not fully understood. Studying environmental changes that took place around the time of the impact may help scientists figure out the answer.

Changing Ecosystems

Bourque and his colleagues analyzed leaf wax *n*-alkanes (a type of hydrocarbon) that had been preserved in ancient fluvial sediments in Chambery Coulee and another site near Saskatchewan's Highway 37 to learn more about how the world changed. These leaf wax compounds, Bourque said, "come in a variety of... chain lengths, and different types of plants produce different ratios of these chain lengths. Typically, aquatic plants will produce shorter chain lengths, whereas terrestrial plants produce longer ones.... So we noticed that there's a shift from more shorter-length plant waxes to longer ones going across the boundary." This change implies that terrestrial plants were becoming more abundant compared with aquatic plants after the extinction event.

This finding aligns with previous research on prehistoric pollen samples, which showed an increase in angiosperm (flowering plant) pollen, especially species similar to today's birch and elm trees, in the time following the extinction event.

Researchers also analyzed the carbon and hydrogen isotopes in the *n*-alkanes, which allowed them to reconstruct changes in the carbon cycle and the water cycle. In contrast to the long-term changes in plant communities they observed after the extinction event, the team did not find obvious long-term changes in precipitation or the carbon cycle subsequent to the event.

So what was responsible for the long-lasting changes in plant ecology? Researchers hypothesized that this burst of terrestrial plant abundance was due to another factor: the sudden disappearance of the dinosaurs. With just about every large terrestrial herbivore wiped from the face of Earth, terrestrial plants flourished.

Chambery Coulee is a window into the deep past, a place that holds the secrets of the mass extinction that ended the age of the dinosaurs 66 million years ago.

Next Steps

Ken MacLeod, a geology professor at the University of Missouri, said he would like to see the paper's line of inquiry expanded to include more samples, across both time and geographic space. More samples from the time period would help provide greater resolution of exactly when these environmental changes occurred, whereas more samples from around the world would help determine how widespread this phenomenon was—did it occur only in southern Saskatchewan, across all of North America, or even perhaps around the entire planet?

Frenchman Valley in Chambery Coulee, Saskatchewan, above, was one of the sites at which researchers traced changes in plant ecology following the Chicxulub impact event. Credit: R. D. Bourque

Bourque had similar thoughts. "Looking at a finer scale across the boundary would be extremely interesting, to try and better estimate what happened over what time period," he said. "And broadening the scope to other sites from the same time period would be incredibly interesting."

MacLeod said there's a lot of interest in improving our understanding of this time period, especially because "the Cretaceous-Paleogene impact is, I think, literally the only event in the Phanerozoic [the past 541 million years] with global-scale implications that manifest on timescales shorter than anthropogenic changes." Studying how Earth systems responded to perturbations in the past, MacLeod said, might help us understand the response of these systems in the present, which is also a period of rapid change.

By **Hannah Thomasy** (@HannahThomasy), Science Writer

Student-Led Diversity Audits: A Strategy for Change

The Radcliffe Camera, originally built to house a science library, is a symbol of the University of Oxford, where geoscience students conducted an innovative diversity audit. Credit: Benjamin Fernando

The underrepresentation of ethnic minorities throughout the geosciences is well documented and just as true at the University of Oxford in the United Kingdom as it is anywhere else. A 2019 report from the university noted that although admission of students from minoritized racial and ethnic backgrounds was disproportionally low university-wide, the Department of Earth Sciences admitted the lowest proportion of Black and non-Asian ethnic minorities—half as many as the next lowest department.

Many frameworks for addressing representation issues shift a disproportionate amount of responsibility to members of these groups by expecting them to both identify and solve the issues they raise. This "minority tax" can unintentionally exacerbate the problems that these initiatives seek to address.

Shifting the Burden of Developing Solutions

In response to this admissions report and the widening attention being paid to issues of diversity in higher education, a group of graduate students from the Department of Earth Sciences at Oxford initiated a student-led diversity audit.

Our aim in executing this audit was to empower students in our community to raise issues that they saw or experienced at the university that burdened ethnic minority students, without the expectation that those students would be required to enact the solutions themselves. Instead, our team would assess the responses and offer suggestions to the faculty with some direction for how they could implement each solution. Key to this plan was engaging white students to assist with brainstorming and developing ideas and in making an extra effort to encourage fellow allies to attend.

We approached this effort from the point of view of concerned graduate students, rather than experts in diversity, equity, and inclusion. As such, we offer this as an example of an experimental project, which has sparked progress from our department so far.

Organizing the Audit Through Focus Groups

Early on, we decided to rely on qualitative rather than quantitative methods for identifying issues. In a community with so few BAME (U.K. terminology for Black, Asian, and minority ethnic) students, anonymization of responses is impossible. We also thought it might be harder to reach conclusive actions strictly from the data provided by surveys; instead, we organized focus groups, which would allow for more nuanced discussion and immediate feedback.

Our main focus group, which took place over part of an afternoon, was open to all students and faculty within our department. About 20 people attended, from undergraduates to professors. The first half of the session was spent on identifying problems; the second half was dedicated to identifying solutions. We followed this session with some small-group and one-on-one discussions to develop specific ideas and address problems related to a particular incident that a participant did not want to air in a bigger group.

From these discussions, we identified 42 specific recommendations for addressing the lack of representation of minoritized students within the Department of Earth Sciences at Oxford. Each recommendation included a description of the rationale for the action, our suggestion on each action's priority, and a recommended timeline. Finally, we presented our report to department faculty and invited them to respond.

Key Themes from the Audit

In June 2020, around 200 geoscience students and faculty from Oxford and the U.K. community attended our announcement and discussion of the report and its findings. The event was held virtually and included the head of our department, as well as representatives from the Geological Society of London and the Royal Astronomical Society.

After presenting our results, an attendee asked us to identify three key messages. Although our key messages are well known to those pursuing more diversity in the geosciences, our audit provided specific supporting examples that helped lead us toward solutions at our university.

The first key message is that the geosciences' ethnic minority student populations are not homogeneous—as a result, neither are the challenges they face, nor the solutions. For example, the underrepresentation of Black British students at Oxford can be traced to a disproportionately low percentage

of Black applicants compared with the U.K. population. British students of Indian heritage, however, apply in roughly the same percentage as exists in the national population but are admitted at lower rates than white or Black applicants with equal qualifications.

Addressing low admissions, then, requires targeted solutions. For Black students, that might mean focusing on outreach and community engagement strategies that acknowledge underlying discrimination in the schooling system [*Joseph-Salisbury,* 2020]. For British Indian students, it likely means thoroughly examining the admissions process for biases.

The second message is that inclusion efforts help everyone. Although our work focused on students from ethnic minorities, we were able to identify the commonalities that different minoritized groups face.

Finally, the idea that diversity is important to recruitment while inclusion is important to retention is partially true but overly simplistic. The separation here neglects many of the crossovers between these concerns. For example, students who feel excluded while obtaining their undergraduate degree will be more challenging to recruit to postgraduate education.

These broader themes led us to our 42 recommendations—including the following two that are focused on adaptations of recruitment and fieldwork.

Recruitment Should Take Cultural Context into Account

Many of us are guilty of assuming that the only significant barrier to increased university admissions of minoritized groups in geoscience majors is a lack of awareness of the field. It's reassuring to think that simply more dedicated outreach and engagement will be enough to boost the diversity of future classes.

The reality is more complex. Some families—particularly first-generation immigrant families that want a more financially secure future for their children—may not see the geosciences as offering as much job security as more traditional careers in medicine or law. Furthermore, they may see the Earth sciences as requiring skills that are niche rather than broadly transferable.

In our report, we suggest that the university address these concerns in several ways, including holding separate parents-only and students-only sessions to encourage questions on unfamiliar subjects with less fear of embarrassment. We also recommend producing an application guide for parents that directly addresses some of these concerns—such as emphasizing the technology and coding skills required of many geoscience careers.

Universities should also be cognizant of students applying from communities that have a politically or historically fraught relationship with geological industry, such as England's Black Country or Indigenous communities in the United States. These students may reject or at least be discouraged from pursuing the geosciences as a topic of study. We recommend that schools seek more input from these communities and find ways to showcase geoscience careers on the other end of the spectrum from natural resource extraction.

Fieldwork Shouldn't Always Require a Field

The challenges and risks of fieldwork are many when it comes to minoritized students—whether racial or ethnic minorities, women, LGBTQ+ people, or those with disabilities. Reduced familiarity with the outdoors has been discussed as one—though certainly not the only—reason for reduced participation in the geosciences by ethnic minorities, who are much more likely in the United Kingdom to be urban based [*Giles et al.,* 2020]. This is an underlying problem that universities are not realistically in a position to address.

In our discussions with faculty about the report, we were quickly able to find many places to work together on the 42 actions we suggested.

What universities can do, however, is put more effort into highlighting the relevance of the geosciences to urban populations. This might be done through discussions of the geoscience contributions to climate change solutions and the United Nations' Sustainable Development Goals. But it can also be done more practically, for example, by highlighting work in urban geology or the applications of civil geophysics and urging the development of urban fieldwork in university courses.

Faculty Responses

Although faculty were invited to our working groups, our group of students sequestered to write the report. Our suggestion for students looking to replicate this process at their own schools is to lay some more groundwork with faculty, such as requesting a private meeting with university leadership before presenting the report publicly. This interaction can help ensure that the report launch is seen as an opportunity to develop new collaborations rather than a time to criticize existing efforts.

In our discussions with faculty about the report, we were quickly able to find many places to work together on the 42 actions we suggested. The department wrote a point-by-point reply just 2 weeks after our report was released, publishing it on the school's website alongside our original report. It highlighted a number of items that as of last July had been initiated or were already underway. For those that the department considered unfeasible, it offered detailed explanations.

These are just first steps, of course. We were able to propel these discussions into a dedicated town hall at AGU's Fall Meeting 2020 to discuss the report and its methodology. Overall, we are encouraged by the responses to our diversity audit at Oxford and optimistic that we have begun a fruitful collaboration with the faculty to continue to address these issues.

Acknowledgments

The author is first and foremost grateful for Gwen Antell's partnership in developing this audit and her invaluable advice in conducting the focus groups and writing the text of the report. The efforts of the University of Oxford's Chris Ballentine, Isobel Walker, and Conall MacNiocaill in preparing the department's response are also deeply appreciated, as are the inputs of all those who participated in our focus groups. I am also grateful to Rebecca Colquhoun for her support in synthesizing ideas for this article.

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▶ Read the article at bit.ly/Eos-diversity-audits

GeoPRISMS: A Successful Model for Interdisciplinary Research

In 1988, 65 scientists from a wide range of disciplines gathered in a meeting room in Irvine, Calif., to discuss ways to advance their understanding of the complex Earth systems called continental margins. These 57 men and 8 women shared a visionary idea: What if the Earth sciences and the ocean sciences, two fields that were traditionally independent and funded separately—and divided by that nebulous boundary that is the shoreline—could be connected? What if terrestrial and marine geoscientists had a better way to share knowledge, communicate ideas, and establish new approaches to investigate the active geological processes shaping continental margins? From that meeting, the concept of an interdisciplinary, integrative, amphibious research program took shape. More than 30 years later, those of us who have been involved in the process are proud to look back on the success born of this idea.

Following that 1988 meeting, it took more than a decade of planning before the first iteration of this effort, called MARGINS, got under way. MARGINS launched in 2000 and was jointly funded by the National Science Foundation (NSF) Earth Sciences and Ocean Sciences divisions. The program started small but quickly gained momentum with a cohort of geophysicists, geochemists, volcanologists, and sedimentologists all eager to develop a common language and work toward the same goals. The range of data collected through MARGINS and, more important, the integration of those data have transformed our knowledge of subduction zones and rifts.

In 2009, NSF acknowledged the success of MARGINS in its Decadal Review and indicated it would support a continuation of these efforts. The community came up with a 10-year plan for a successor program, called GeoPRISMS (Geodynamic Processes at Rifting and Subducting Margins), to carry on the mission of MARGINS to foster collaborative, shoreline-crossing science. The scope of GeoPRISMS, which began in 2010 and will last through this year, expanded beyond MARGINS to address novel scientific questions with direct societal impacts—such as questions related to understanding geologic hazards and managing coastal environments—and to include study of inactive and exhumed margins as well as the role of surface processes in the evolution of continental margins. The program would also expand engagement of early-career scientists to increase diversity and inclusion in these fields.

GeoPRISMS addressed novel scientific questions with direct societal impacts, such as questions related to understanding geologic hazards and managing coastal environments.

The GeoPRISMS science plan included two broad initiatives: to study Rift Initiation and Evolution (RIE) and Subduction Cycles and Deformation (SCD). The initiatives targeted active and passive margins at five primary sites around the world: the Eastern North American Margin and the East African Rift System for the RIE initiative; and Cascadia, New Zealand, and the Alaska-Aleutian subduction zone for the SCD initiative. Scientists engaged in GeoPRISMS research addressed five science themes that encompass commonalities among continental margin processes: the origin and evolution of continental crust; fluids and melts and their interactions; tectonic-sediment-climate interactions; geochemical cycles; and plate boundary deformation and geodynamics.

This article provides a glance at some of the distinctive elements of GeoPRISMS that have enabled fundamental advances in scientific understanding while also contributing to building a strong, vibrant research community.

Participants in the GeoPRISMS Subduction Cycles and Deformation Initiative met to discuss research progress in Redondo Beach, Calif., in 2015. Credit: Anaïs Férot, GeoPRISMS

Supporting the Next Generation of Geoscientists

A strength of GeoPRISMS has been its steadfast support of early-career researchers and their professional development through a range of experiential and educational activities. Early-career scientists—defined here as undergraduates, graduates, postdocs, assistant researchers, and pretenure faculty members—have had a central place within the program and have been heavily engaged in planning processes and research projects. They have received financial support to attend GeoPRISMS meetings and workshops and invitations to lead breakout groups, convene workshops, and present keynote lectures.

Since 2010, 300 early-career researchers have received networking support and background training at premeeting symposia in preparation for subsequent discussions at planning and implementation meetings that might otherwise have been overwhelming. Student competitions held each year during the annual GeoPRISMS town hall event at AGU's Fall Meeting gave exposure to the research of more than 200 students, who had chances to network, engage with peers, and meet NSF representatives.

GeoPRISMS has also supported 14 postdoctoral researchers in conducting up to 2 years of multidisciplinary research at U.S. institutions. These scholarships encouraged individuals to further develop research skills, diversify their expertise, and establish peer relationships. The scholarship program has proven successful: Everyone who completed their postdoctoral appointment has since moved into subsequent faculty or research positions.

GeoPRISMS has funded a number of large, long-duration data collection efforts called community projects, including the Cascadia Initiative, the Alaska Amphibious Community Seismic Experiment, and the Eastern North American Margin Community Seismic Experiment. Data sets from these projects have been made publicly available immediately, and many projects have been funded subsequently to use those data.

The Distinguished Lectureship Program offered opportunities for students to interact with experts and be exposed to unfamiliar areas of science and research.

Expeditions associated with the community experiments, from marine seismic data acquisitions to onshore field campaigns, provided unique opportunities for early-career scientists to receive training, gain experience, and develop skills in interdisciplinary science. Hundreds of researchers have participated in all aspects of onboard and field science activities, including instrument preparation, deployment, and recovery; data acquisition and processing; and live communicating about research efforts.

Raising Geoscience Awareness

GeoPRISMS developed and maintained an Education & Outreach program geared toward engaging the wider science community and the public. The GeoPRISMS Distinguished Lectureship Program (DLP), for example, played an instrumental role in disseminating new findings and illustrating the depth and breadth of the program.

Starting in 2010, the DLP sponsored 10 lecture series articulated around GeoPRISMS research topics. Through the program, 36 scientists from a wide range of disciplines and career levels—half of them women—traveled across the United States to share with public audiences the cutting-edge science they conducted through GeoPRISMS. All told, 226 institutions, from moderate-sized community and liberal arts colleges to museums and public venues, hosted DLP speakers, and more than 10,000 people have attended these lectures.

The benefits of the DLP went beyond sharing programmatic updates. The lecture series offered opportunities for students to interact with experts and be exposed to unfamiliar areas of science and research. In conjunction with their lectures, DLP speakers often set aside time to meet with students and answer questions regarding career and research opportunities, in some cases stimulating students' interest—and infusing a sense of possibility—in pursuing alternative paths in science.

The DLP also helped improve representation of women in science, technology, engineering, and mathematics (STEM) fields: As highlighted in feedback from host institutions and attendees, exposure to successful female scientists discussing their accomplishments inspired female early-career researchers to pursue education in the geosciences. The program extended the reach and inclusiveness of GeoPRISMS science as well by bringing high-caliber speakers to institutions that were geographically isolated, such as in Hawaii and Puerto Rico, or that had little or no budget to bring in guest speakers. Such visits helped spur new collaborations, strengthen professional networks, and inspire new avenues of research and communication among students, other early-career scientists, and more established researchers.

The Legacy of GeoPRISMS

As GeoPRISMS comes to a close after its run of more than 10 years, the time is right to consider its legacy and look ahead to work still to be done to advance geoscience understanding and further develop a diverse community of researchers.

GeoPRISMS executed the vision of an interdisciplinary program while demonstrating the value of science driven by a community of researchers. The program has supported a wide range of integrated research approaches and leveraged strong international collaborations, thereby developing fundamental understanding of shoreline-crossing Earth systems and their importance in global processes, as well as of resource distribution and geohazards. The high-quality data sets collected by GeoPRISMS investigators are appropriately cataloged, archived, and accessible to the community to support and promote the principles of findable, accessible, interoperable, and reusable (FAIR) data and to establish a robust data legacy.

GeoPRISMS researchers have been synthesizing the resulting science products to be compiled in a special volume celebrating a decade of accomplishments (bit.ly/GeoPRISMS-volume). This issue of *Eos* highlights several efforts that have led to discoveries made via the GeoPRISMS subduction and rift initiatives, communicating the breadth and importance of the program's science to a broad audience.

Two decades of collaboration through the MARGINS and GeoPRISMS programs have forged solid relationships between NSF's Ocean Sciences and Earth Sciences divisions. In its 2020 report about the future of the NSF Division of Earth Sciences, the National Academies of Sciences, Engineering, and Medicine (NASEM) recognized the potential of research connecting terrestrial and ocean environments to advance knowledge about many key research topics, such as the dynamics of Earth's interior and mitigating risks from earthquakes, eruptions, and tsunamis. And NASEM encouraged efforts in the scientific community to further support interdisciplinary research that capitalizes on connections across divisions at NSF.

The grassroots efforts that have stressed the importance of decisionmaking by a research community, rather than by only a handful of scientists, have allowed GeoPRISMS to lead the way among peer research programs, such as the late NSF EarthScope program, in defining and carrying out community experiments and expeditions. GeoPRISMS effectively brought together and trained a broadly interdisciplinary group of scientists to be the next generation of practitioners in a highly collaborative culture.

As revealed by current GeoPRISMS demographics, the program has also fostered a research community balanced with respect to gender and career status. These same demographics also reveal, however, that there is still much work to be done within the geosciences to address long-standing inequities and shortcomings in representation and inclusivity. Research programs built upon GeoPRISMS's successful model should lead the way in developing best practices to attract, train, and retain BIPOC (Black, Indigenous, and people of color) students and scholars. This is an essential shift to ensure that the geosciences become and remain truly just, inclusive, equitable, and diverse.

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Geodetic observations collected during back-to-back decadal research campaigns have revealed crucial new insights into the start–stop and slow-motion behavior of subduction zones.

SLIPPING AND LOCKING IN EARTH'S EARTHQUAKE FACTORIES

By Noel Bartlow, Laura M. Wallace, Julie Elliott, and Susan Schwartz

Downtown Anchorage, Alaska, was devastated by shaking during the second-largest earthquake ever recorded, which occurred along the Alaska–Aleutian subduction on 27 March 1964. Credit: Everett Collection Historical/Alamy Stock Photo

What do 1952, 1960, 1964, 2004, and 2011 have in common? In each of those years, a catastrophic subduction zone earthquake and tsunami—collectively the five largest earthquakes ever recorded—occurred somewhere around the world. Subduction zones, where one tectonic plate dives below another in fits and starts on its way into Earth's mantle, create the largest and most destructive earthquakes and tsunamis on our planet. Revealing the dynamics of how subduction zones slip and the factors that influence them is crucial in assessing the hazards they represent.

In the time between large earthquakes, called the interseismic period, the interface between downgoing and overlying plates can become locked due to friction, accumulating stresses for hundreds of years or more, most of which will ultimately be released in future earthquakes (Figure 1). Our understanding of subduction zone slip behavior has been transformed over the past 2 decades, thanks in large part to the advent of high-precision Global Navigation Satellite Systems (GNSS; GPS is one of four GNSS systems) and other techniques from geodesy, a field focused on measuring subtle displacements of Earth's surface. Geodetic studies enable delineation of locked portions of subducting plate interfaces in unprecedented detail and have revealed regions in many subduction zones worldwide where future large earthquakes may nucleate.

During interseismic periods, subduction zones are not static but, rather, host a variety of smaller, slow-slip events (SSEs) [*Schwartz and Rokosky*, 2007, and references therein], the discovery of which in the late 1990s provided a new perspective on the mechanics of subduction zones. SSEs involve a few to tens of centimeters of slip along a plate interface over days to years, rather than over the seconds to minutes timescales of regular earthquakes. Imaged using high-precision geodesy, SSEs are essentially slow-motion earthquakes that do not create damaging seismic waves or tsunamis. However, because SSEs add stress to locked fault zones, they may trigger damaging earthquakes, as has been suggested in the cases of the 2011 Tohoku-Oki earthquake in Japan and Chile's 2014 Iquique earthquake [*Ito et al.*, 2013; *Socquet et al.*, 2017]. Earthquakes can also trigger SSEs, which may in turn trigger further earthquakes.

The study of slow-slip behavior is still young and we do not yet fully understand all the possible interactions between slow-slip and regular earthquakes, but recent observational advances have led to great progress. Much of this progress was spurred by the National Science Foundation's (NSF) GeoPRISMS (Geodynamic Processes at Rifting and Subducting Margins) program (2010–2021) and its predecessor, the MARGINS program (2000–2010). Both programs supported studies of subduction zones off Costa Rica, Nankai (Japan), Cascadia, Alaska, and New Zealand. Together these locales exhibit virtually every known flavor of subduction slip behavior, megathrust locking characteristics, and subduction margin physical properties (e.g., rate of plate convergence, amount of sediment input, age of subducting plate, etc.). This variety has provided outstanding opportunities to resolve the physical processes leading to slow slip and to large megathrust earthquakes and to investigate relationships among SSEs, subduction plate interface locking, and large earthquakes.

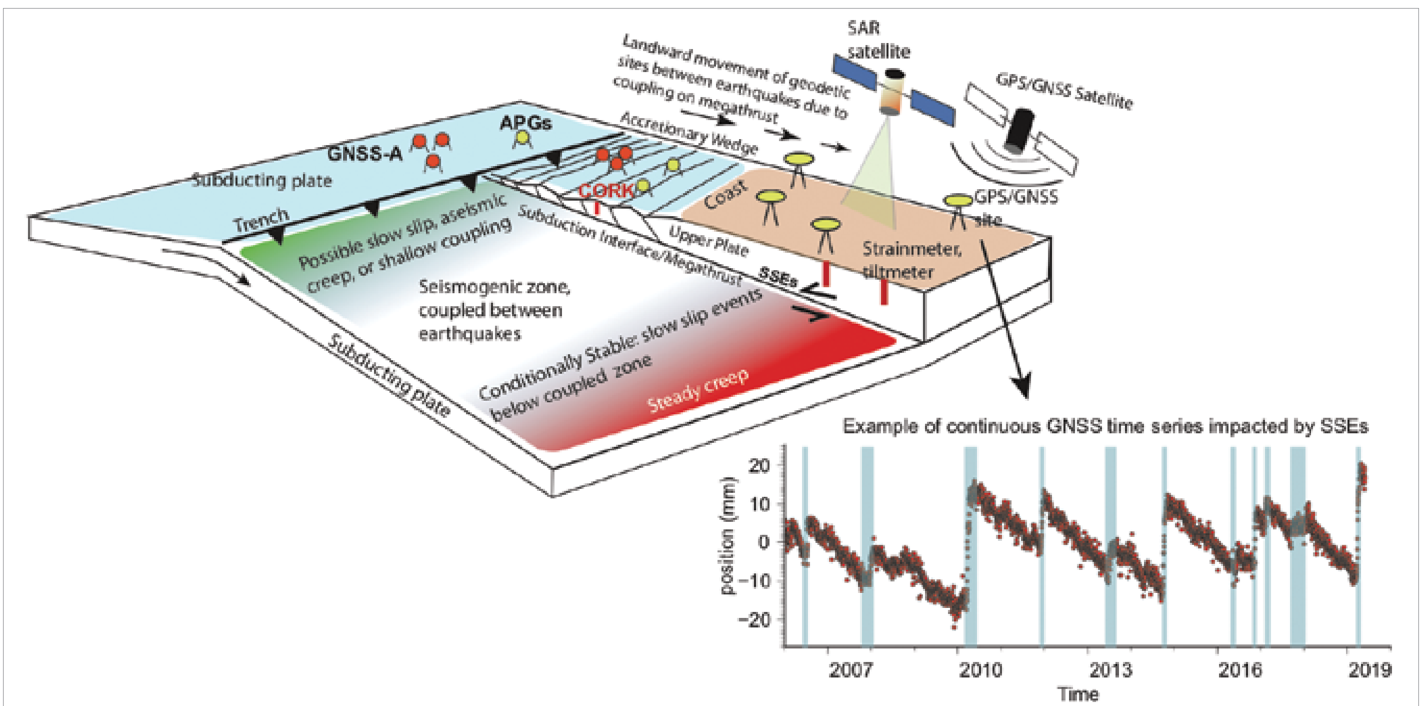

Fig. 1. Geodetic measurements that can be made at subduction zones to discern megathrust locking and slip behavior include those from Global Navigation Satellite Systems (GNSS), synthetic aperture radar (SAR), absolute pressure gauges (APGs), and borehole instruments (such as the Circulation Obviation Retrofit Kit, or CORK, offshore borehole instrument). The graph at bottom right shows an example of a continuous GNSS site time series of subduction zone slip affected by slow-slip events (SSEs, marked with shaded blue bars). Typical megathrust behavior is shown, but specific behavior at subduction zones globally can vary from what is represented here.

Here we highlight examples of progress in our understanding of slip behavior at the five subduction zone focus sites of the NSF programs.

The Nankai Trough

This subduction zone off southwestern Japan has a long history of producing great earthquakes (magnitude > 8.0). Numerous Japanese-led geodetic studies have indicated that the subduction interface in the source region of past great earthquakes along the Nankai Trough is currently locked, suggesting that elastic strain accruing right now will be relieved in future megathrust earthquakes. Studies at Nankai have benefited from seafloor GNSS-Acoustic sensors that enable centimeter-level resolution of horizontal movements of the seafloor. These movements reveal the degree of shallow locking near the trench, and tracking them will inform tsunami hazard assessments in future earthquakes.

The Nankai Trough is also the site of a diverse range of geodetically detected SSEs, many of which are accompanied by tectonic tremor that largely occurs downdip of (i.e., deeper along the plate interface) the earthquake-producing seismogenic zone, which is locked between earthquakes (Figure 1). Tectonic tremor is a low-amplitude, long-duration seismic signal that is depleted in high-frequency energy compared with typical earthquakes. Some of these SSEs are shorter, lasting a few days to weeks, while others last a year or more [*Hirose et al.,* 2010]. Recently, observations from instrumented seafloor boreholes revealed episodic SSEs near the trench, updip of (i.e., shallower than) the locked seismogenic zone [*Araki et al.,* 2017]. Potential triggering relationships between these SSEs and earthquakes are not yet clear, and continuing studies—for which Japan is well equipped—will be important in establishing what, if any, relationships exist.

The Middle America Trench

This rapidly converging subduction zone is responsible for generating earthquakes of magnitude 7 and greater about every 50 years beneath the Nicoya Peninsula, Costa Rica [*Protti et al.,* 2014]. Because of the regularity of large earthquakes here, the presence of land very close to the trench, and the presumption that the region was late in its earthquake cycle when the MARGINS program was getting under way, Costa Rica was one of the first regions chosen as a focus site for the program. With support from MARGINS, GPS/GNSS and regional seismic observations covering the Nicoya Peninsula began in 1999 and continue today. These 2 decades of instrumental coverage captured the most recent large earthquake, a magnitude 7.6 event on 5 September 2012, allowing the late interseismic period leading up to the event, as well as the coseismic and postseismic phases of the earthquake cycle, to be well recorded.

Geodetic observations during the late interseismic phase led researchers to identify a region of the plate interface that appeared frictionally locked and that subsequently matched closely with the area that ruptured during the 2012 Nicoya earthquake [e.g., *Protti et al.,* 2014]. However, areas of the plate interface that experienced SSEs prior to the 2012 earthquake did not rupture during the main shock [*Dixon et al.,* 2014]. If this behavior is characteristic of other subduction zones, it suggests that better monitoring of SSEs could provide valuable information for earthquake and tsunami forecasting.

Cascadia Subduction Zone

Large earthquakes occur every few hundred years in the Cascadia subduction zone, most recently in January 1700. Geodetic models broadly agree on the presence of a strongly locked zone located mainly offshore in the region where past earthquake ruptures are inferred to have occurred. How close to the surface this locking extends, which will significantly influence the size of future tsunamis, is poorly determined, thus limiting scientists' ability to forecast hazards.

The GeoPRISMS program has enabled installation of GNSS-Acoustic sites offshore Cascadia that should soon help answer this question, delineating the updip limit of locking. Meanwhile, onshore GPS/GNSS data from southern Cascadia have revealed a newly identified phenomenon of offshore earthquakes triggering changes in plate interface locking [*Materna et al.,* 2019], raising the possibility that plate locking varies in time, even during interseismic periods. This observation challenges the common assumption that interseismic locking is temporally steady and motivates a need to monitor locking in subduction zones for potential changes over time.

Geodetic data have also revealed that like the Nankai subduction zone, the Cascadia subduction zone features deep SSEs that are strongly associated with tectonic tremor [*Rogers and Dragert,* 2003]. The influence of these SSEs and tremor on the timing of large

IF THIS BEHAVIOR IS CHARACTERISTIC OF OTHER SUBDUCTION ZONES, IT SUGGESTS THAT BETTER MONITORING OF SSES COULD PROVIDE VALUABLE INFORMATION FOR EARTHQUAKE AND TSUNAMI FORECASTING.

earthquakes is unclear and deserves further study.

The Alaska–Aleutian Subduction Zone

The second-largest earthquake ever recorded, the magnitude 9.2 Prince William Sound earthquake of 1964, occurred on this subduction zone, which has since generated other events of magnitude 7–8 and greater. Geodetic studies have revealed strong locking in areas that slipped during the 1964 earthquake [e.g., *Li et al.,* 2016; *Elliott and Freymueller,* 2020]. Some areas that slipped less during the 1964 event appear to be partially locked or continuously slipping today, suggesting that some locked patches may persist through multiple earthquake cycles.

SSEs also occur along the Alaska subduction zone, generally as multiyear events downdip of the locked zone, although at least some of these seemingly long SSEs may comprise bursts of multiple shorter subevents [*Li et al.,* 2016; *Rousset et al.,* 2019]. As with other subduction zones, the updip extent of locking is poorly resolved because of a lack of seafloor data. A recently funded GeoPRISMS project installed three seafloor GNSS-Acoustic sites, which offer improved resolution of shallow locking during the period leading up to the 2020 magnitude 7.8 Simeonof earthquake.

Spahr Webb (standing) and Pete Liljegren from Columbia University's Lamont-Doherty Earth Observatory do final checks on an APG/ocean bottom seismometer instrumentation package for a 2018 deployment offshore New Zealand's Hikurangi subduction zone. Credit: Neville Palmer, GNS Science

GEODETIC STUDIES HAVE REVEALED STRONG LOCKING IN AREAS OF THE ALASKA SUBDUCTION ZONE THAT SLIPPED DURING THE 1964 EARTHQUAKE.

The Hikurangi Subduction Zone

Onshore GNSS data sets have revealed that locking at the Hikurangi subduction zone, beneath New Zealand's North Island, varies significantly along the subduction interface. The largest area of locking occurs beneath the capital city of Wellington and has substantial earthquake and tsunami hazard implications for residents.

A large variety of SSEs, occurring at a range of depths and with widely varying duration, recurrence, and magnitude characteristics, have also been observed on the Hikurangi subduction zone [*Wallace,* 2020]. And intriguing interplays between SSEs and recent New Zealand earthquakes have been seen, including unprecedented and widespread triggering of SSEs following the 2016 magnitude 7.8 Kaikōura earthquake [*Wallace et al.,* 2018]. Absolute pressure gauges (APGs) deployed on the seafloor near the northern Hikurangi margin recorded centimeter-scale vertical deformation during these SSEs, revealing that SSEs can propagate close to the seafloor. GeoPRISMS has enabled additional deployments of GNSS-Acoustic instruments and APGs to investigate offshore SSEs and locking at Hikurangi.

Putting It All Together

A wide range of subduction slip behavior is displayed at the GeoPRISMS and MARGINS focus sites, but a few observations are common to all or most of them. Geodetically imaged fault locking has generally coincided with areas that have ruptured in the past. In the case of Costa Rica, it coincided with the eventual ruptures of then-future earthquakes. A variety of slow-slip types clearly accommodate large portions of plate motion in these subduction zones, although the details vary widely among different regions. Slow slip also typically occurs outside regions of strong fault locking; however, we cannot rule out the possibility that seismic ruptures (and tsunamigenesis) could occur in regions currently dominated by slow slip.

Despite advances in detecting SSEs, significant gaps exist in our ability to detect smaller and shorter transient events and to reconcile seismological and geodetic observations of slip events. More widespread use of instruments like borehole tiltmeters, strainmeters,

and pressure sensors is required to bridge these gaps. Recent evidence also indicates that locations of strongly locked regions may vary over time; detecting these "coupling transients" (and resolving the processes that produce them) requires improvements in data analysis and modeling techniques.

The value of seafloor geodetic sensors to resolving near-trench subduction deformation processes is now well demonstrated at MARGINS and GeoPRISMS focus sites and should be more widely applied at other subduction zones. Addressing knowledge gaps about crustal deformation throughout the subduction earthquake cycle will require long (decades and beyond), uninterrupted time series of data from numerous subduction zones, both onshore and offshore. This need underscores the importance of maintaining continuous geodetic and seismological infrastructure. It will also require that geodetic observations be further integrated with a range of other geophysical, geological, laboratory, and modeling studies.

MARGINS and GeoPRISMS have enabled great advances in our ability to observe subduction zones and to understand how they operate and the hazards they pose. Future programs should ensure continued progress in this societally important area of research and generate new discoveries about the physical processes underpinning our planet's largest earthquake and tsunami factories.

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EARTH'S VOLATILE BALANCING ACT

By James D. Muirhead, Samer Naif, Tobias P. Fischer, and Donna J. Shillington

How do greenhouse gases and water circulate from minerals deep below Earth's surface into the atmosphere and oceans—and then back again? Our understanding continues to evolve.

Steam and gas rise from a volcano on the island of Java, Indonesia. Credit: iStock.com/Russian Labo

Earth's hot, pressurized interior is composed primarily of rock that, despite being solid, contains vast stores of fluids rich in carbon and dissolved gases. Unlike the free-flowing waterways of Earth's surface or the groundwater just beneath, however, these subsurface fluids have long been trapped within minerals deep inside the planet, some since its formation 4.5 billion years ago. Indeed, there is likely more water stored in Earth's interior than is on its surface, constituting a global ocean in the rock below our feet [*Hirschmann,* 2006].

We refer to these deep fluids as volatiles—the most common of which include water, carbon dioxide (CO_2), and sulfur dioxide (SO_2)—because they readily turn to gas in Earth's near-surface region. However, down below, they often remain chemically bound to minerals or in a liquid state due to the massive pressures they experience. Deep volatiles play critical roles in driving volcanic and plate tectonic processes on our planet. For example, the presence of water in rock reduces the temperatures required to melt rock, which promotes the formation of magmas that feed volcanic eruptions. Deep volatiles can also weaken and damage rocks, allowing Earth to deform more readily by flowing or fracturing, and they influence the occurrence of earthquakes.

UNDERSTANDING HOW VOLATILES CYCLE THROUGH OUR PLANET IS CRITICAL FOR IMPROVING OUR KNOWLEDGE OF EARTH'S TECTONIC AND VOLCANIC PROCESSES AND OF THE EVOLUTION OF ITS CLIMATE.

Vigorous fumarole activity releases gases that produce sulfur deposits at Kiska volcano in the western Aleutian Islands. Credit: Tobias Fischer

Volatiles escape Earth's interior when they are dissolved in magmas that ascend toward the surface in volcanic regions. As magmas cool and solidify, either as erupted lavas or as igneous rocks emplaced in the crust, they release their dissolved gases, which can then be expelled through fumaroles near volcano summits or through seafloor vents (often called black smokers for the dark billowing plumes of precipitating minerals that pour from them). If, as magma rises to the near surface, the dissolved volatiles transform into gas bubbles that rapidly expand, they can catastrophically fragment magma to drive explosive volcanic eruptions.

Gases expelled in volcanic regions—water vapor, CO_2, SO_2, methane, and others—can become incorporated into surface water and into minerals within crustal rocks. They can also, however, collect and reside in our atmosphere for up to thousands of years (although human activities today release much greater amounts of these gases into the atmosphere). The concentrations of these gases in our atmosphere play critical roles in controlling global temperatures.

Understanding how volatiles cycle through our planet's atmosphere, oceans, and rocky interior is thus critical for improving our knowledge of Earth's tectonic and volcanic processes, as well as of the evolution of its climate both today and through geologic time. Scientific advances in the 20th century provided a foundation for investigations into deep volatile transport during the National Science Foundation–funded MARGINS program (2000–2010) and its successor GeoPRISMS (Geodynamic Processes at Rifting and Subducting Margins) program (2010–2021). Studies occurring within or alongside these programs have since revolutionized our understanding of where volatiles are located, how they are transported from the

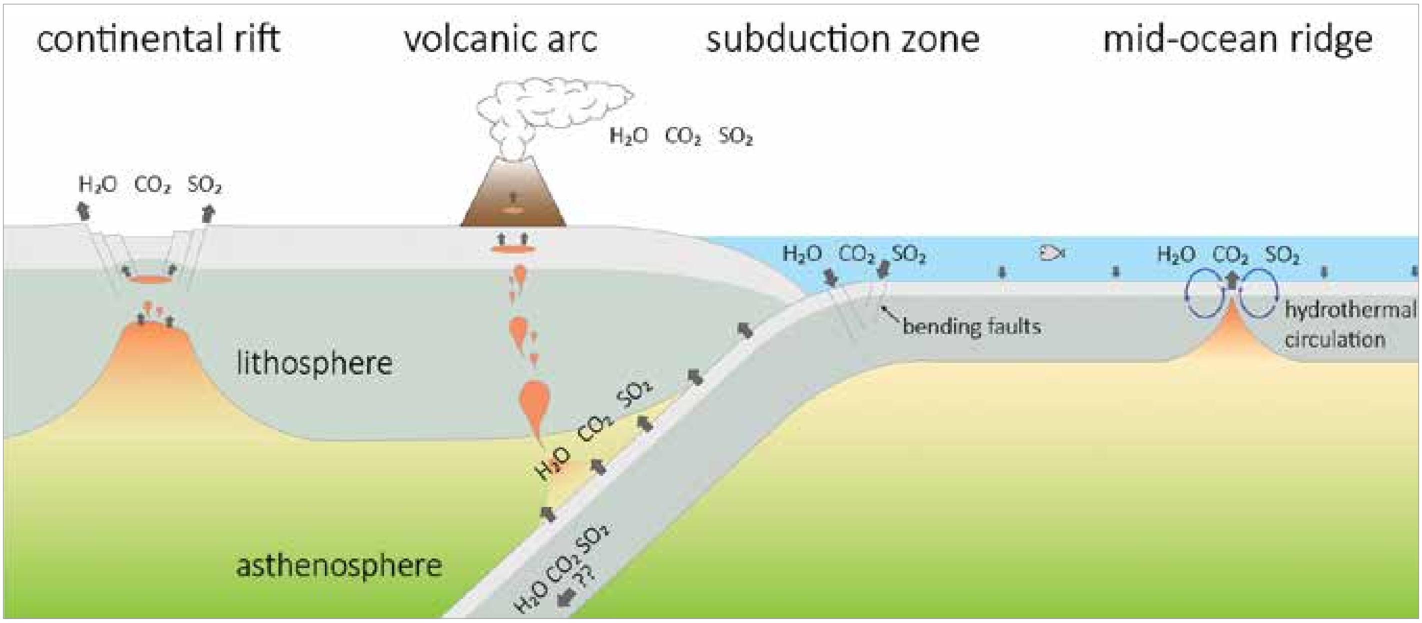

Fig. 1. This simplified illustration shows a selection of volatile inputs to and outputs from Earth's interior at various tectonic settings. Common volatile species like water (H_2O), carbon dioxide (CO_2), and sulfur dioxide (SO_2) are incorporated into the lithosphere below the seafloor as water circulates through faults or is trapped in ocean sediments. Magmatic, volcanic, and tectonic processes at volcanic arcs, continental rifts, and mid-ocean ridges help to liberate volatiles trapped in rocks and release these gases into the atmosphere. This figure does not show all volatile species or all of the natural processes controlling their migration. The influences of human activities on the release of greenhouse gases like CO_2 into Earth's atmosphere are also not shown.

ocean and the atmosphere into the lithosphere (comprising the crust and the uppermost mantle), and how they are incorporated into magmas on their journey back to Earth's surface.

Origins of Volcanic Arc Volatiles

The origins of magmatic volatiles remained a controversial topic until relatively recently. Early studies in the 1960s suggested that water dissolved in magma was primarily meteoric, originating as rainfall that circulated within the crust before being incorporated into magma.

Beginning in the late 1980s, scientists recognized another, potentially deeper source for volatiles at subduction zones (Figure 1). At these convergent tectonic plate boundaries, where one lithospheric plate sinks beneath another, volatile-laden material is recycled from the shallow and surficial Earth into its deep interior. Most of Earth's subaerial volcanoes (i.e., those that are exposed to the atmosphere) are found along volcanic arc systems above subduction zones. By examining the abundances of carbon, nitrogen, and noble gases like argon and helium, researchers demonstrated that most of the CO_2 and nitrogen released at these volcanoes originated from the subducting plates [*Marty and Jambon*, 1987]. Later studies showed the same for magmatic water at volcanic arcs [*Giggenbach*, 1992].

INTERACTIONS BETWEEN SEAWATER AND ROCKS AT MID-OCEAN RIDGES LEAD TO THE FORMATION OF HYDROUS MINERALS THAT ULTIMATELY STORE COMPONENTS OF SEAWATER WITHIN OCEANIC LITHOSPHERE.

It is now known that the volatiles released at arc volcanoes were originally incorporated into the lithosphere largely through processes occurring within the seafloor millions of years earlier. The global mid-ocean ridge system, a 65,000-kilometer-long divergent plate boundary that accounts for most of Earth's volcanism, is key in volatile assimilation. These ridges are localities of intense hydrothermal circu-

lation of seawater through the crust, where fluids migrate through developing faults and fractures and fluid convection is driven by heating from submarine volcanism and magmatism. The resulting interactions between seawater and rocks at mid-ocean ridges lead to mineral alteration and the formation of hydrous minerals that ultimately store components of seawater within oceanic lithosphere [*Alt*, 1995].

Sediments deposited and rock formed atop seafloor crust as a result of sedimentary processes in ocean basins also store such elements as hydrogen, sulfur, and carbon [*Jarrard*, 2003]. And immediately prior to subduction, a final and critical hydration stage results from the bending and faulting of the lithosphere at subduction margins, which enables deeper and more pervasive hydration [*Ranero et al.*, 2003]. Following subduction, some of these volatiles are later released back into the atmosphere as water, CO_2, SO_2, and other gases because of magmatic and volcanic processes.

THE APPARENT DEFICIT IN CARBON OUTPUTS BASED ON CURRENT OBSERVATIONS AND CALCULATIONS SUGGESTS THE LIKELIHOOD OF A SOURCE OF DEEP CARBON.

Tracking Volatiles Through Subduction Zones

The potential role that faults play in allowing seawater to infiltrate and hydrate oceanic mantle was of wide interest to the MARGINS research community, and investigations of the topic continued during the GeoPRISMS program. Recent work has since confirmed that faults do indeed penetrate the lithosphere, drive fluids into the crust, and likely hydrate the crust and the uppermost mantle [e.g., *Grevemeyer et al.*, 2018]. This work has provided more accurate constraints on the volumetric inputs and outputs of volatiles at subduction zones.

These studies also revealed that although some volatiles delivered into the deep Earth at subduction zones are released back into the atmosphere and the ocean at arc volcanoes, large volumes also remain trapped in the subsurface. Studies now point to higher volatile storage resulting from subduction than previously thought, with these volatiles incorporated into minerals in the crust and the mantle.

Bending-related hydration prior to subduction could contribute the largest amount of water entering subduction zones. Some theoretical and observational studies suggest that volatiles may penetrate tens of kilometers into the oceanic mantle because of this bending [*Cai et al.*, 2018], with the oceanic mantle storing 4 times more water than subducting oceanic crust. However, contrasting studies suggest that volatile penetration is limited to the top few kilometers of oceanic mantle [*Korenaga*, 2017], leaving the subducting mantle with 4–8 times less water than the overlying oceanic crust. As such, bending-related hydration of the oceanic crust and mantle remains poorly constrained. Refining the large uncertainties in water fluxes at subduction zones is critical for balancing the global water budget.

Missing Sources of Deep Carbon

Because CO_2 is a greenhouse gas that plays a key role in controlling Earth's climate, the scientific community is particularly interested in balancing the outputs and inputs of deep carbon in addition to studying water fluxes. The amount of CO_2 in Earth's atmosphere has remained within a narrow range (typically 150–400 parts per million) throughout the past 10 million or so years, conditions that have maintained an "icehouse climate" (as distinct from "greenhouse climate" periods in the more distant past).

Stable atmospheric CO_2 levels require a balance between deep carbon outputs and inputs. But compilations of carbon fluxes reveal that the amount of carbon transported into Earth's interior by subducting plates significantly exceeds the amount released at volcanic arcs [*Kelemen and Manning*, 2015]. These observations suggest that the crust and the mantle at subduction zones sequester substantial quantities of carbon, and likely also other critical volatile components.

The apparent deficit in carbon outputs based on current observations and calculations further suggests the likelihood of a currently unrecognized source of deep carbon. Earth's global mid-ocean ridge system is one possible explanation. At mid-ocean ridges, carbon is extracted from mantle rock when this rock melts and is then released into the ocean during submarine volcanism. Quantifying CO_2 fluxes from these settings

has been the focus of numerous studies over the past few decades [*Wong et al.,* 2019]. Recently, however, these studies have started to converge on a common value for the total carbon flux from mid-ocean ridges that is too low to make up the apparent carbon deficit, hinting that there are still other critical sources responsible for the remaining carbon.

The GeoPRISMS program targeted studies at other potential sources of deep carbon. In particular, the role of continental rifts (e.g., the East African Rift System) has been of significant interest. Not only are large magma volumes produced at these settings, but they also represent locations where Earth's continents split apart through the formation of deep cracks and faults (Figure 1).

Recent studies show that in addition to volcanoes, widespread faulting at continental rift systems provides pathways for deep CO_2 to reach the surface. Furthermore, compared with mid-ocean ridges, continental rifts occur in comparatively ancient continental lithosphere, thereby tapping volumetrically large carbon stores accumulated over billions of years [*Muirhead et al.,* 2020].

Improving the Picture of Earth's Volatiles

Over the past few decades, much progress has been made toward constraining global water and carbon fluxes in and out of Earth's interior. But significant gaps remain in our understanding, particularly of carbon emissions from volcanically and tectonically active regions as well as of fluxes of other important volatiles such as nitrogen, methane, and halogens.

Continental rifts arguably represent the biggest source of uncertainty in global carbon flux estimates [*Plank and Manning,* 2019]. Quantifying total CO_2 fluxes from continental rifts is thus a critical endeavor for future deep carbon studies. Other uncertain sources of global CO_2 outputs, all of which also require further study, include regions of diffuse volatile degassing via soils, volcanic lakes, and volcanic aquifers. However, our ability to measure volatile fluxes at these settings is limited because of their size and complexity. The 3,000-kilometer-long East African Rift System, for example, features thousands of faults. Each fault releases a relatively small amount of gas, but cumulatively they may represent a significant volume of carbon release.

Technological advances using satellite- and unoccupied aerial vehicle–based remote sensing, combined with high-resolution geophysical studies and geodynamic models, may help track emissions from these environments and are needed to obtain a more complete picture of volatile fluxes on Earth. Quantifying these fluxes is relevant for many current and future community scientific efforts and is essential in developing a comprehensive understanding of past and current environmental change on our planet as well as of Earth's volcanic and seismic hazards.

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BREAK IS HARD TO DO, CONTI

By Lindsay L. Worthington,
Brandon D. Shuck,
Anne Bécel,
Zachary C. Eilon, and
Colton Lynner

A decade-long research collaboration has revealed that the split between Africa and North America roughly 200 million years ago was more drawn out than previously thought.

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The cyclic amalgamation and rupture of supercontinents is one of Earth's fundamental tectonic processes, ultimately affecting nearly every aspect of the planetary surface on which we live, from global climate to species evolution, through its control of land distribution, ocean circulation, atmospheric composition, and other factors. Continental and oceanic crust today preserves signatures of these make-and-break cycles, which have occurred several times through geologic time. But the evidence is rarely easy to interpret, leaving many questions outstanding.

For example, continents are really hard to break, and scientists are still trying to explain how they do. Models imply that plate tectonic forces alone are not strong enough to pull continents apart, so additional mechanisms must contribute. In many places where continents have broken apart, geoscientists have inferred a role for extensive magmatism. Magmas may have enabled continental breakups by heating and weakening continental tectonic plates [*Buck*, 2006], but it is often not clear where, when, and how much magma was involved.

Roughly 200 million years ago, the world's most recent supercontinent, Pangea, began to rupture. The eastern North American continental margin (ENAM), stretching from Florida to Nova Scotia, offers glimpses into the conditions leading to Pangea's demise, with records of extension (i.e., the stretching or

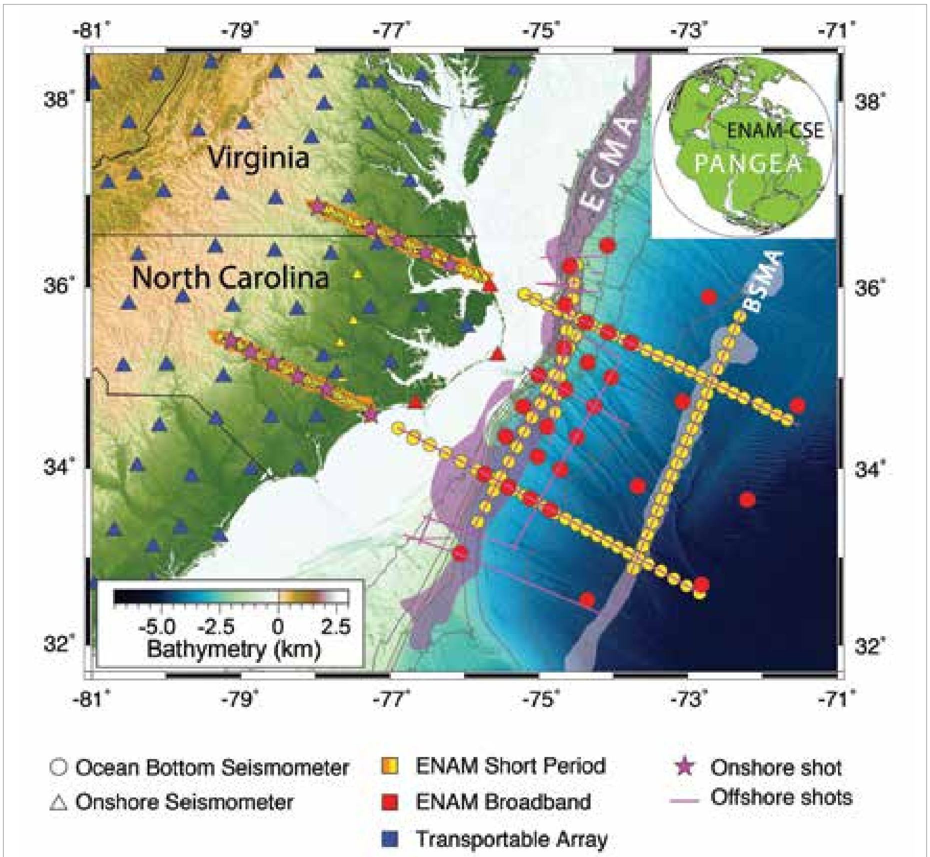

Fig. 1. The data acquisition footprint of the Eastern North American Margin Community Seismic Experiment (ENAM-CSE) off the coast of North Carolina is shown here (modified from Lynner et al. *[2020]). The experiment included a 1-year broadband seismometer array deployment, collection of wide-aperture active source seismic profiles to constrain crustal structure across and along the margin, and multichannel seismic reflection imaging expanded upon the EarthScope Transportable Array footprint. The extents of the East Coast Magnetic Anomaly (ECMA) on the continental slope and of the Blake Spur Magnetic Anomaly (BSMA) on the abyssal plain are indicated. The inset map shows a representation of Pangea roughly 200 million years ago created by the PLATES Project at the University of Texas at Austin.*

pulling apart of rock) and magmatism frozen into the geologic structure of the current passive margin. Through extensive input from the research community, the GeoPRISMS (Geodynamic Processes at Rifting and Subducting Margins) program, a decadal initiative sponsored by the National Science Foundation, chose the ENAM as a focus site at which to investigate the role of magmatism during the initial rifting of Pangea and in subsequent rift evolution.

In 2014–2015, the ENAM Community Seismic Experiment (ENAM-CSE; Figure 1) [*Lynner et al.,* 2020] provided the first immediately open data sets focused on multiscale seismic imaging over a passive margin. The CSE encompassed a roughly 500-kilometer-wide section of the margin, extending farther seaward from the North Carolina coastal plain than previous studies and offering a complete picture of the Pangean breakup. The experiment involved multiple shoreline-crossing, controlled-source seismic profiles and an array of broadband ocean bottom seismometers, allowing for high-resolution, along-margin comparisons of crust and upper mantle structure (Figure 1).

The amphibious multiscale experimental focus and open-access data arrangement have since led to a wealth of new findings related to the formation and evolution of the ENAM, forcing scientists to reconsider much of what we thought we knew about continental breakup and the formation of this passive margin.

Magmatism Splits a Supercontinent

Passive margins exist at transitions between continents and oceans where no active tectonic plate boundary occurs. Previous work has suggested that continental rifts, where landmasses split apart, and the margins they leave behind can be classified as either magma rich or magma poor. The model for magma-rich margins imagines voluminous bursts of magmatism injected into the crust, quickly weakening and eroding the existing continent and triggering breakup over a very short time frame.

The ENAM has long been a type example of a magma-rich margin [*Holbrook and Kelemen,* 1993]. It is characterized by the presence of voluminous lava flows such as the Central Atlantic Magmatic Province (CAMP) and volcanic deposits that line the edge of the continental shelf, forming the East Coast Magnetic Anomaly (ECMA; Figure 2), which spans the length of the margin offshore [*Greene et al.,* 2020]. However, new seismic and magnetic data collected during the ENAM-CSE suggest that the ENAM doesn't entirely fit the mold of a typical magma-rich margin. Detailed computer models of the crustal structure created from these data show that magmatic intrusions into the lower continental crust during the breakup of Pangea were limited to distinct patches beneath the continental margin, rather than being widespread [*Shuck et al.,* 2019]. And modeling of magnetic data shows that volcanism associated with the initial formation of the ECMA was emplaced over millions of years, rather than during a short pulse, and that extension rates during the earliest stages of breakup were far slower than previously estimated [*Davis et al.,* 2018].

A short but intense magmatic event that occurred about 200 million years ago, the CAMP is the most areally extensive large igneous province recorded in Earth's history, spreading 10 million square kilometers across the heart of Pangea, with records found in Africa, North America, and South America. This feature has long been thought of as a driving factor in continental breakup, although recent results suggest a more nuanced role. Early extension [e.g., *Withjack et al.,* 2012] may have created the conditions for widespread decompression melting of the mantle that resulted in the CAMP [*Marzen et al.,* 2020]. The subsequent emplacement of CAMP volcanics, in turn, then facilitated further extension and magmatism that eventually gave way to successful rifting.

A Prolonged Breakup

It is surprisingly difficult to put a finger on the timing and geographic location of the continental breakup that created the ENAM. Traditional viewpoints suggest that the ECMA marks the boundary between stretched continental crust and the earliest oceanic crust that formed after breakup and that it therefore represents the location of the continental rupture and initial seafloor spreading. Given the volcanic nature of the rift, scientists expected the CSE data to show a gradual decrease in crustal thickness seaward of the ECMA to about 7 kilometers, the average value for normal oceanic crust. Instead, the data reveal a roughly 200-kilometer-wide anomalous zone of thin and heavily faulted "proto-oceanic" crust [*Bécel et al.*, 2020] (Figure 2). Although the crust in this region appears to be similar to normal oceanic crust, it is thinner and rougher and has faster seismic velocities [*Shuck et al.*, 2019].

Studies using the mineral content of crystallized magmas to infer ancient mantle temperatures were synthesized with seismic results to help explain this mysterious zone of igneous crust. Together these data indicate that a 15- to 20-kilometer-thick layer of lithosphere (dark green in Figure 2) acted like a lid, preventing melting of the shallow mantle. As a result, rather than quick establishment of a mid-ocean ridge that channels deep melt toward a spreading axis, diffuse melt instead percolated upward slowly throughout the stretching plate [*Shuck et al.*, 2019]. The rough texture of the proto-oceanic upper crust and the slow rates of extension here indicated by seismic reflection imaging support this interpretation [*Bécel et al.*, 2020].

Relatively warm mantle temperatures beneath Pangea during its breakup, inferred from petrological models and chemical signatures of CAMP basalts, show that this lithospheric lid consisted of continental rock, likely a stubborn remnant of the supercontinent. Evidently, the continental plate had not yet fully ruptured at the ECMA during formation of the anomalous region of early oceanic crust, and the battered lithosphere was hanging on by a thread.

If the current African and North American plates did not fully separate at the ECMA, when and where did they finally break apart? Another prominent magnetic anomaly, the Blake Spur Magnetic Anomaly (BSMA), marks the rapid onset of normal oceanic crust about 200 kilometers seaward of the ECMA. Findings from the CSE suggest that complete rupture of the continental lithosphere finally occurred at the BSMA, accompanied by a magmatic pulse and the initiation of normal seafloor spreading in the central Atlantic.

The rifting process was likely delayed because of the strong, thick lithosphere of the supercontinent Pangea, which long resisted the intense but slow stretching forces despite the presence of abundant magmatism. But the hot mantle asthenosphere gradually eroded the lithosphere until persistent deformation and magmatism eventually delivered the final blow. And about 168 million years ago, the fate of Pangea was set, the Atlantic Ocean was born, and Africa and North America began their slow drift apart, which continues to this day.

Graduate student Kate Volk watches the response from the subbottom profiler aboard the R/V Endeavor *during the ENAM-CSE (top left). Students Kara Epple, Matthew Karl, and Sasha Montelli help deploy an 8-kilometer-long seismic streamer on the R/V* Marcus Langseth *(top right). Engineers and technicians from Woods Hole Oceanographic Institution recover a broadband ocean bottom seismometer aboard the R/V* Endeavor *(bottom left). Beatrice Magnani and Dan Lizarralde recover one of the 80 seismometers deployed for 1 month in North Carolina and Virginia in 2014 (bottom right). Credit (clockwise from top left): Gary Linkevich, Donna Shillington, Anne Bécel, Yanjun Hao*

The rifting process was likely delayed because of the strong, thick lithosphere of Pangea, which long resisted intense but slow stretching forces.

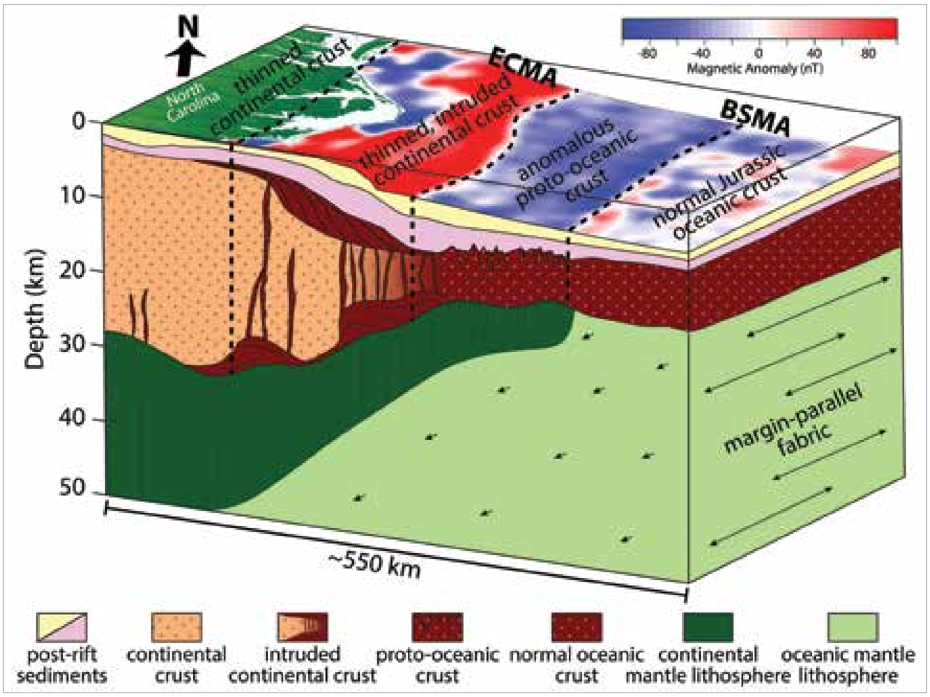

Fig. 2. This schematic shows tectonic domains present along the ENAM. Offshore magnetic anomaly data lie over seafloor bathymetry data. Results from the ENAM-CSE suggest that the full lithospheric rupture of Pangea occurred along the BSMA, not the ECMA as previously thought. Magnetic anomaly data are from version 3 of the Earth Magnetic Anomaly Grid (2–arc minute resolution); bathymetry data are from the ETOPO1 Global Relief Model. Both data sets are publicly available from the National Centers for Environmental Information.

Active Processes on a Passive Margin

The multiscale observational focus in studies of the ENAM supported and promoted by GeoPRISMS has not only recast our views on the Mesozoic rifting of Pangea but also shed light on far more recent processes. In particular, the ENAM region hosts several active geohazards, and it appears to encapsulate more complex mantle dynamics (see Figure 2) than suggested by the research community's previous understanding.

Lessons from the ENAM demand that we rethink simplistic paradigms for the ongoing breakup of the African continent.

New seismic imaging of the shallow sediments across much of the ENAM-CSE study area indicates a high potential for submarine landslides and associated geohazards, including tsunami generation [*Hill et al.,* 2018]. Passive margins have long been recognized as hosting significant earthquakes. Present-day crustal stresses along the ENAM are sufficient to create earthquakes with widespread shaking and damage, as demonstrated by the 2011 magnitude 5.8 earthquake in Mineral, Va. [*Wolin et al.,* 2012]. Ongoing and active asthenospheric flow beneath the margin (both onshore and offshore) [e.g., *Lynner and Bodmer,* 2017], putatively driven by gradients in mantle temperature and viscosity, may exacerbate both sets of hazards by creating localized mantle upwellings and downwellings that affect surface topography and intraplate stresses.

A Modern Analogue in East Africa

Our updated views of the ancient rifting of Pangea influence our understanding of the second GeoPRISMS rifting focus site, the currently active East African Rift (EAR). Often thought of as the archetypal "narrow rift," the EAR is cited as a region where magmatism is splitting a modern continent in two.

However, lessons from the ENAM demand that we rethink simplistic paradigms for the ongoing breakup of the African continent. Current plate motions show broad extension that encompasses much of the Ethiopian plateau, well beyond the fault-bounded main rift. And new seismic data [*Petruska and Eilon,* 2020] from the rift flanks reveal high temperatures and, likely, mantle melt at roughly 100-kilometer depth, extending well beyond the main locus of recent (younger than 10 million years) extension.

Furthermore, ongoing EAR rifting and changes in extension rates from north (i.e., the Afar region) to south (i.e., in Kenya) allow us to see how rifting progresses episodically through time [e.g., *Ebinger et al.,* 2013], grounding the evidence of similar waxing and waning in the rate of Pangean rifting 200 million years ago. If these dynamics persist, the EAR may provide a modern analogue to ENAM rifting, whereby continental thinning becomes widely distributed, delaying or forestalling eventual breakup.

A Formative Legacy

The impact of GeoPRISMS's focus on rifting extends beyond the scientific accomplishments it has fostered. The program's rifting initiative, including the ENAM-CSE, has revitalized a community of researchers by involving them in fieldwork, seminars, miniworkshops, and conferences; more than 700 attendees have attended ENAM-focused meetings, for example. Since the conclusion of the ENAM-CSE, more than 200 presentations have showcased undergraduate and graduate research conducted under the umbrella of GeoPRISMS at major national conferences, and numerous papers on the topic have been published in that time.

The GeoPRISMS program has thus not only been instrumental in driving improved understanding of a fundamental Earth process; it has also been formative for a new generation of scientists, whose professional networks and approach to collaborative research and community-driven science will carry forward into the next several decades of investigations into continental rifting.

Acknowledgments

The ENAM-CSE study area includes traditional lands and waters of many Indigenous Peoples, including the Lumbee, Skaruhreh/Tuscarora, Hatteras, Roanoke, and Chesapeake territories. We thank the captains and crews of the R/Vs *Marcus G. Langseth* and *Endeavor*, the Seismic Source Facility, the Ocean Bottom Seismograph Instrument Pool (OBSIP; now OBSIC), and all technical personnel and student volunteers for their efforts during data acquisition. We gratefully acknowledge the ENAM-CSE principal investigators: Harm van Avendonk, Donna Shillington, Beatrice Magnani, Dan Lizarralde, Brandon Dugan, Matt Hornback, Steven Harder, Anne Bécel, Jim Gaherty, Maureen Long, Gail Christeson, Lara Wagner, and Maggie Benoit. Data from the ENAM-CSE are available at the Marine Geoscience Data System. See *Lynner et al.* [2020] for full data set citations. EarthScope Transportable Array data are available at the IRIS (Incorporated Research Institutions for Seismology) Data Management Center (virtual network code US-TA).

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▶ Read the article at bit.ly/Eos-continental-breakup

How Some Trees Survive the Summer Dry Season

An important component of Earth's hydrologic cycle is transpiration—the movement of water through plants. Because transpiration affects near-surface temperatures, streamflows, and the productivity of ecosystems, understanding potential sources of subsurface moisture and how plants use them is crucial for developing accurate dynamic vegetation and land surface models. Our knowledge of these processes, however, is far from complete, in part because they are hidden below the ground.

To better understand where trees get their water from, *Hahm et al.* studied Oregon white oaks (*Quercus garryana*), deciduous hardwoods that thrive in Pacific Northwest locales with thin soils underlain by highly weathered bedrock. Because these gnarled oaks have deep taproots, scientists have long assumed they draw upon groundwater to survive the long dry seasons typical of the Mediterranean climate in their range.

To test this hypothesis, the researchers used a combination of isotopic analyses and hydrologic measurements to characterize the sources of water used by the oaks at a study site in Northern California's Eel River Critical Zone Observatory. The data showed that despite the presence of groundwater just a few meters below the surface, these trees during summer depend primarily on water drawn from the soil and the deep unsaturated zone, the region of weathered bedrock from which groundwater recedes at the beginning of the dry season. These results indicate that the trees' use of rock moisture may be due to the groundwater's low oxygen content and location within bedrock of low permeability.

Researchers studied Oregon white oaks like those pictured here to test the hypothesis that they required groundwater during the dry summer months. Credit: Colin Durfee, CC BY 2.0 (bit.ly/ccby2-0)

The findings highlight that not all groundwater is accessible to plants, even when it is within reach of their roots, and suggest that patterns of water uptake by oaks in Mediterranean climates may be site specific. Because forests are commonly located on hillsides with thin soils that overlie weathered bedrock, the results further suggest that extraction of rock moisture may be a globally important process.

As one of a growing number of studies demonstrating that trees can tap into water stored within weathered bedrock, this paper has important implications for forest management, according to the authors. The results emphasize the need to better understand the distribution of water in weathered bedrock on a landscape scale to improve predictions of how forests will respond to extended drought. (*Water Resources Research*, https://doi.org/10.1029/2020WR027419, 2020) **—Terri Cook,** *Science Writer*

A Global Look at Surface Soil Organic Carbon

Healthy soil is paramount to life on Earth. In addition to its importance in agriculture, soil is the foundation for almost every terrestrial ecosystem on the planet. Soil organic carbon (SOC) is frequently used as a gauge of soil health, it plays an important role in terrestrial carbon cycling, and it carries huge implications for climate change adaptation. Understanding these dynamics on a planetary scale will be vital as humanity attempts to feed a growing population under increasing stress from a warming planet.

In a new study, *Endsley et al.* used remote sensing to study surface SOC dynamics globally, drawing data from NASA's Soil Moisture Active Passive (SMAP) satellite, which combines radiometer measurements of Earth's surface low-frequency microwave emissions with modeling to calculate soil moisture and the freeze-thaw state. In particular, SMAP's microwave radiometer data can be combined with a physical model of plant carbon uptake and soil decomposition to estimate the global terrestrial carbon budget in the SMAP Level 4 Carbon (L4C) product. The team used SMAP L4C in combination with other satellite data, such as vegetation observations from Moderate Resolution Imaging Spectroradiometer instruments, to create a model that would specifically characterize SOC.

The result is a global estimation of SOC to a depth of 5 centimeters with a horizontal resolution of 9 square kilometers. The scientists compared their estimates with prior measurements and soil inventory records of SOC and found that their model generally agreed well with them. The researchers say that the new model will allow them to monitor seasonal and annual changes in SOC and will also offer a view of how ecosystems and the planet at large respond to floods, droughts, and other short-term events. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2020JG006100, 2020) **—David Shultz,** *Science Writer*

Dylan de Jonge/Unsplash

Determining Dissolved Organic Carbon Flows into the Gulf of Alaska

The variety of land cover and soil types draining into the Gulf of Alaska and coastal estuaries is illustrated in this watershed within the Héen Latinee Experimental Forest bordering Lynn Canal to the north of Juneau, Alaska. Credit: Richard Edwards, U.S. Forest Service

Amid ongoing climate change, understanding how and where carbon is moving across ecosystems has become a top research priority. This type of "carbon accounting" helps scientists determine where the planet is sequestering and releasing atmosphere-warming carbon compounds and is especially important at the boundaries between different ecosystems.

In a new study, *Edwards et al.* investigate how rivers in western Canada and southeastern Alaska transport dissolved organic carbon and fresh water into the Gulf of Alaska. The study region, which spans from northern British Columbia to the southwestern corner of the Yukon Territory, represents an incredibly complex confluence of glaciers, forests, mountains, and plateaus with river systems that drain into bays, fjords, and channels before reaching the Pacific Ocean.

To build the model of carbon flux, the researchers combined a digital elevation model with estimated shapes of watershed boundaries and glacier extents as well as gridded data representing mean monthly runoff. To calculate the total amount of freshwater runoff, they used a distributed climate water balance model calibrated with measurements taken from watersheds in the study area.

The scientists calculated that overall, the region exports 430 cubic kilometers of fresh water and 1.17 teragrams of dissolved organic carbon annually to the Pacific Ocean. Their model shows that watershed type, location, and flow rate are important variables that control the spatial and temporal patterns of carbon flux. The team says that despite the region's immense size and importance for both commercial fishing and climate, the Gulf of Alaska has been chronically understudied compared with other sections of the North American coastline. The new results highlight the significance of the region and provide a starting point for unraveling the complexity of the dynamic ecosystems and their effects on climate and humanity. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2020JG005725, 2021) **—David Shultz,** *Science Writer*

Researchers Unearth Bedrock Carbon and Water Dynamics

On Earth's surface, countless plants and animals grow and move, taking in and releasing carbon. Beneath all that, the soil teems with insects, microbes, and fungi, all bustling and respiring. The bedrock farther below the surface, in contrast, may seem sterile, although it, too, often hosts life. Trees and other plants commonly work their roots all the way down into bedrock fissures, bringing along accompanying microbes. This deep rooting markedly changes the chemistry of that fractured bedrock and the water that flows through it.

In a new study, *Tune et al.* investigated carbon cycling and fluxes within weathered bedrock several meters beneath an old-growth forest in Northern California. They note patterns in carbon dynamics that followed seasonal cycles. In the wet season, up to about 80% of the carbon produced in the bedrock dissolved into water and accelerated further weathering in the rock and soil. In the dry season, bedrock respiration continued as trees drew water from deeper bedrock zones when the soil above dried out.

The researchers also note that dissolved inorganic carbon (DIC) flowed downslope at their hillside study site and accumulated in the groundwater at the hill's base and that DIC originating from the weathered bedrock accounted for 63%–80% of the total amount exported from the hillslope. This process thus carries the effects of bedrock weathering on the slope beyond the immediate ecosystem.

This research contributes to the study of an underresearched carbon source that has yet to be adequately factored into scientists' understanding of the global carbon cycle. Future research, they suggest, should expand on these findings to look at conditions in other seasons, ecosystems, and scales to illuminate the role of weathered bedrock and deep rooting in carbon cycling and climate dynamics. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2020JG005795, 2020) **—Elizabeth Thompson,** *Science Writer*

Juno Maps Water Ice Across Northern Ganymede

Jupiter's moon Ganymede is the largest planetary satellite in the solar system. It's also one of the most intriguing: Ganymede is the only moon with its own magnetic field, it is the most differentiated of all moons, and it likely possesses a subsurface ocean of liquid water. It was studied by the early Jupiter flybys made by the Pioneer and Voyager spacecraft, but our understanding today rests largely on observations made by NASA's Galileo orbiter from 1995 to 2003.

Mura et al. now report some of the first in situ observations of Ganymede since the end of the Galileo mission. They used the Jovian Infrared Auroral Mapper (JIRAM) on board NASA's Juno spacecraft to take images and spectra of the moon's north polar region. On 26 December 2019, Juno passed Ganymede at a distance of about 100,000 kilometers, enabling JIRAM to map this region at a spatial resolution of up to 23 kilometers per pixel.

As Juno flies past Ganymede, the spacecraft can observe physical locations on the moon's surface from a variety of angles. By comparing the brightness of these regions across a range of observation and illumination geometries, the authors developed a photometric model for Ganymede's surface reflectance. They observed that wavelength-dependent reflectance relationships sometimes break down in the vicinity of relatively fresh craters, perhaps because of a larger average size of ice grains in these regions.

Combining their model with spectral observations of the 2-micrometer water ice absorption band allowed the authors to map the distribution of water ice in the north polar region. Where these estimates overlapped with maps derived from Earth-based telescopic observations, the researchers found largely good agreement. This congruence enabled them to extend the global water ice map for Ganymede to much more northerly latitudes.

Observations in other spectral bands also revealed the presence of nonwater chemical species on the surface of Ganymede, including possible detections of hydrated magnesium salts, ammonia, carbon dioxide, and a range of organic molecules. The authors note that 2020 offered additional opportunities for Juno to make polar observations of Ganymede, as does 2021, and suggest that continuing observations from JIRAM will help set observation strategies in future observing campaigns like the Europa Clipper and Jupiter Icy Moons Explorer (JUICE) missions. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2020JE006508, 2020) **—Morgan Rehnberg,** *Science Writer*

Untangling Drivers of Ancient Hurricane Activity

Forecasts of hurricane frequency in a warming world remain unclear. Although scientists believe climate change will increase storm intensity, the data are murkier about whether climate will drive more hurricanes in the future. For coastal communities, understanding long-term hurricane trends is consequential: The Congressional Budget Office estimates that tropical cyclones cost the U.S. economy $54 billion annually.

To inform understanding of climate's role in past and future hurricane activity, *Wallace et al.* investigated whether climate explains patterns of long-term hurricane occurrence recorded in sediment cores. Using sandy layers in cores from South Andros Island in the Bahamas as a reference, the authors developed a model to mimic hurricane patterns captured in the sediments over thousands of years. They then generated 1,000 different "pseudorecords" from the same climate simulation, each of which represented a theoretical hurricane history at a single location.

Each individual record contained intervals of active and quiet hurricane activity that resembled the real patterns in the Bahamas sediment cores. If climate were responsible for these intervals, then the periods of activity and quiet should have occurred at approximately the same times in all the pseudorecords. However, the researchers found that the intervals occurred at very different times in each record, leading them to conclude that the hurricane patterns over the past millennium observed in the sediment cores more likely resulted from randomness than from climate variations. That is not to say that hurricanes occur randomly, the researchers note, but rather that climate does not clearly explain the pattern seen in any single sedimentary record.

This image, captured by the European Space Agency's Sentinel-3 satellite, shows the massive extent of Hurricane Dorian, one of the most powerful Atlantic hurricanes on record, as it passed over the Bahamas in September 2019. Credit: European Space Agency, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

The authors inferred that if randomness shapes individual paleohurricane records, then no single location history can implicate climate as the driver of storm patterns. The results thus highlight the need for broader data compilations to tease out climate's role in long-term hurricane activity. (*Geophysical Research Letters*, https://doi.org/10.1029/2020GL091145, 2021) **—Aaron Sidder,** *Science Writer*

Can Satellites Fill Gaps in Agricultural Water Monitoring?

As Earth's population continues to increase and anthropogenic climate change threatens the habitability of parts of our planet, freshwater management is becoming a life-or-death issue for millions. Agriculture uses more of Earth's fresh water than any other sector, primarily for crop irrigation. In places where water is scarce, policymakers are eager to regulate water usage and incentivize more conscientious practices.

Key to advancing these goals, however, is accurately measuring how much water farmers are using. Installing metering devices on irrigation wells is one potential solution, but farmers may not cooperate with these efforts for fear of being charged for drawing too much water. As a result, metering remains rare in rich countries and is almost nonexistent in low-income areas.

An alternative solution that many scientists have proposed is using satellite remote sensing to try to monitor irrigation water usage. But in a new meta-analysis of numerous past studies spanning 1980–2020, *Foster et al.* suggest that uncertainties in remote sensing methodologies for this purpose remain large and may lead to substantial welfare losses for farmers.

A field in southern Alberta, Canada, is irrigated. Credit: Marcia O'Connor, CC BY 2.0 (bit.ly/ccbyy2-0)

A major goal of the new study was to examine how past research validated satellite estimates of water use, particularly how they compared with in situ measurements. Of 26 studies that sought to use satellite data to estimate irrigation water use, only 7 compared findings with measurements collected on the ground at spatial scales relevant to a single field or farm. Furthermore, the results from this small group of validated studies showed that there were large differences—between 20% and 60%—between the satellite estimates and farmers' actual water use.

The authors also calculated the impact that these errors would have on both farmers' incomes and water systems. They show that water use measurement errors could have severe impacts on agricultural profitability and could reduce the ability to effectively manage scarcity and competition over water resources. The authors conclude that remote sensing should not be seen as a quick fix to long-standing challenges of in situ water monitoring and that greater transparency is needed about uncertainties in these methods and their implications for water policy. (*Water Resources Research,* https://doi.org/10.1029/2020WR028378, 2020) **—David Shultz,** *Science Writer*

A Thirstier Atmosphere Will Increase Wildfire Risk out West

Recent years have seen the largest, most destructive wildfires on record in California. Accompanying these extreme events have been extreme levels of evaporative demand—the degree to which the atmosphere "wants" to evaporate water from plants and the ground, regardless of how much water is available.

A new analysis of global climate model simulations by *McEvoy et al.* suggests that evaporative demand will increase in California and Nevada through the end of the century, driving increased risk of more extreme wildfires and drought.

High evaporative demand—a thirstier atmosphere—can boost wildfire danger by drying out vegetation and making it more flammable. Previous research has explored how climate change will affect fire risk in the California-Nevada region, but the specific influences of future changes in evaporative demand have been unclear.

The researchers used a tool called the Evaporative Demand Drought Index to explore short-term (2-week) changes in evaporative demand that could affect fire risk. They also used the tool to examine longer-term changes in evaporative conditions that could help drive multiyear droughts.

The analysis predicts that by the end of this century, short-term extremes in evaporative demand in the California-Nevada region will become 6–10 times more common during summer and 4–6 times more common during autumn. This increase—driven primarily by rising air temperatures spurred by climate change—will significantly boost the risk of extreme wildfires. The researchers also show that the likelihood of extreme multiyear droughts will increase, potentially posing threats to water supplies in the region.

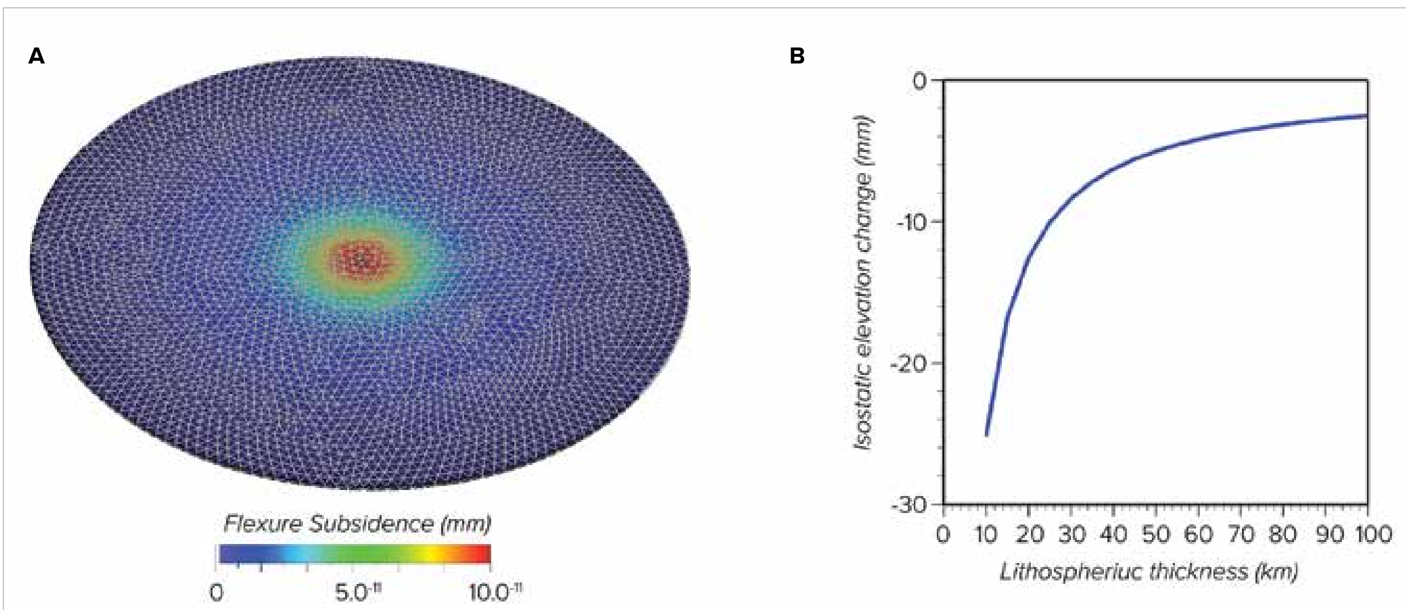
These new findings could help inform development of long-term strategies for wildfire and water resource management in California and Nevada. (*Earth's Future*, https://doi.org/10.1029/2020EF001736, 2020) **—Sarah Stanley,** *Science Writer*

Water Stress Controls the Capacity of the Terrestrial Carbon Sink

Satellite observations over the past nearly 4 decades have captured changes in plant photosynthetic activity tied to increased greenness, concurrent with increasing atmospheric carbon dioxide. Using an improved light use efficiency model and hydrometeorological data (e.g., air temperature, vapor pressure deficit, and root zone soil moisture), *Madani et al.* estimated the evolution of spatially varying gross primary productivity (GPP) globally. The results show higher GPP in the middle and high latitudes, counterbalanced by accelerated decreases at lower latitudes (10°N–10°S), including the Amazon, Congo, and Southeast Asian rain forests.

The increases in GPP at higher latitudes result from warmer temperatures and longer growing seasons, a negative climate feedback. The decreases in the tropics' GPP result from increased atmospheric water stress, further enhanced by reductions in soil moisture during episodic drought, a positive climate feedback. The emergence of water stress at higher latitudes could switch regions of negative climate feedback to positive feedback, accelerating the global downward trend in carbon uptake by plants in the future. This study demonstrates the strong coupling between the water and carbon cycles and highlights water stress controls on the terrestrial carbon sink. (https://doi.org/10.1029/2020AV000180, 2020) **—Ana Barros**

Going Down: How Do Cities Carry That Weight?



The weight of cities might matter either in bending of the lithosphere or in more local isostatic ("floating") adjustment between fault blocks. (a) Modeling of flexure shows that a city-sized load produces only a trivial effect, but (b) isostatic subsidence of a local fault block could reach appreciable maximum values depending on local lithospheric thickness. Credit: Parsons, 2020

Most everyone knows that humans affect their environment, but our thinking usually focuses on domains like the atmosphere or oceans. *Parsons* provides an intriguing look at an Earth-system linkage that gets little attention: the direct impacts of humans on the solid Earth. Focusing on the Bay Area in California, he shows that the mass added by building cities can cause modest but appreciable subsidence, something that should be folded into assessment and planning for sea level rise. It will be interesting to see this sort of analysis done for other tectonic settings, particularly low-lying conurbations where even small changes in relative sea level matter a great deal. (https://doi.org/10.1029/2020AV000277, 2020) **—Peter Zeitler**

Atmospheric Sciences

Employer: FM Global
Position: Post-doctoral Fellowships – Weather and Climate Risks
Location: Norwood, Massachusetts

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Requirements:

Candidates will evaluate, develop, and implement techniques and models that will lead to impactful improvements in risk analytics and loss prevention for atmospheric and climate-related perils. Strong desire to expand their research experience beyond academia and bring expertise and innovative leadership in the following research areas:

- Severe Weather (severe convection, hail, winter storms, nor'easters)
- Tropical Cyclones
- Wildfire
- Climate Change

Required:

- PhD degree in atmospheric or environmental science (or related quantitative field)
- Broad physical and process-level understanding of at least one of the following core research areas: severe weather, tropical cyclones, wildfire, climate change
- Solid knowledge of the fundamentals of climate change including uncertainties and impacts for at least two (preferably more) key perils: major precipitation, drought, wildfire, riverine/coastal flooding, sea level rise, tropical cyclones, and severe weather
- Demonstrated experience using or developing global and/or regional climate models, analyzing output from global climate model ensembles, and combining large atmospheric datasets in formats including NetCDF, HDF, and GRIB.
- Strong analytical skills and solid knowledge of probability and statistics
- Hands-on experience using, developing, and evaluating statistical and numerical models
- Experienced writing shell scripts and using APIs for process automation. Excellent programming skills in at least two programming languages including Python, R, Matlab, Fortran
- Excellent oral and written communication and presentation skills. Demonstrated efficiency communicating highly technical and scientific insights to non-technical audiences

Desired:

- Solid research record (including publications) and demonstrated expertise on natural hazards for the following key perils: severe weather, tropical cyclones, wildfire, climate change
- Experience and working knowledge of using observations for model calibration and statistical downscaling techniques
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Employer: University of Southern Mississippi
Position: Asst. or Assoc. Professor of Ocean Engineering
Location: Stennis Space Center, Mississippi; Gulfport, Mississippi

The Division of Marine Science in the School of Ocean Science and Engineering (SOSE) at The University of Southern Mississippi invites qualified applicants for a full-time, 9-month, tenure-track faculty position in Ocean Engineering at the assistant or associate professor level to begin in Fall 2021. Rank and salary will be commensurate with experience.

The successful candidate will have the opportunity to contribute to the continued development of the undergraduate Ocean Engineering program, which started in 2017, and lead its ABET accreditation. Moreover, the candidate is expected to develop a strong, externally funded research program, publish peer-reviewed literature, mentor students, participate in undergraduate instruction and develop courses in their area of study. The candidate should demonstrate the potential to contribute across disciplines and promote the continued interdisciplinary growth of the academic and research programs within the SOSE.

The SOSE includes two academic divisions, Marine Science and Coastal Sciences, and several R&D centers. The Division of Marine Science is based at the NASA's John C. Stennis Space Center. Stennis Space Center is a "federal city" that boasts the world's largest concentration of oceanographers and hydrographers. Marine Science faculty benefit from close working relationships with on-site federal agencies, including the Naval Research Laboratory-Stennis Space Center, the Naval Oceanographic Office, the Naval Meteorology and Oceanography Command, the USGS, and NOAA including its National Data Buoy Center and the National Centers for Environmental Information.

Marine Science (under)graduate programs extend across traditional marine science emphasis areas in biological, physical, chemical, and geological oceanography, as well as hydrographic science and undergraduate ocean engineering. Marine Science faculty and graduate programs are based out of Stennis Space Center. The Marine Science and Ocean Engineering undergraduate programs are delivered at the USM Gulf Coast Campus in Long Beach, MS as well as at USM's main campus in Hattiesburg, MS. The Long Beach campus is near the Port of Gulfport, which is the home port for USM's R/V Point Sur and the new UNOLS Regional Class Research Vessel R/V Gilbert R. Mason. The Port of Gulfport also features the Marine Research Center, which has a state-of-the-art fabrication lab, testing tank, and laboratory space.

Applicants must hold a Ph.D. in engineering or a related field and have research experience related to the ocean. The successful candidate will be required to pass a NASA background security check to work at Stennis, and a USM employment background check. Preference will be given to candidates with experience in developing academic programs and curriculums. The candidate has participated in an ABET accreditation process. The candidate should have post-doctoral research experience, a demonstrated record of scholarship, service, grant development, communication, and commitment to diversity, and has experience in managing a research group. The candidate should have a national or international reputation for excellence in their discipline.

Applications must be submitted through the jobs.usm.edu candidate portal (req1742). Review of applications begins 3/15/2021 and continues until the position is filled, with an anticipated start date of 8/2021. For questions, please contact the chair of the search committee, maarten.buijsman@usm.edu.

Employer: Washington University
Position: Postdoctoral Position in Data Visualization for Planetary and Space Sciences
Location: Saint Louis, Missouri

The Department of Earth and Planetary Sciences at Washington University in Saint Louis seeks a motivated postdoctoral research associate to manage a unique data visualization program within the Fossett Laboratory for Virtual Planetary Exploration. The Fossett Lab is a leader in the development of applications and outreach experiences that leverage Augmented Reality (AR) technology for education and research in Earth, planetary, and space science. The successful candidate will collaborate with the Fossett Lab Director to build and maintain AR experiences that serve the needs of Washington University

instructors and scholars, and coordinate educational and outreach activities with students, faculty, administrators, and alumni.

The candidate selected for this position will also conduct research as an associate of the McDonnell Center for the Space Sciences (MCSS), and will contribute to this vibrant research community studying planetary materials, surfaces, and processes. In their application materials, the candidate should describe their research interests and list potential collaborators from among the faculty fellows of the MCSS.

Candidates must have a PhD in Earth, planetary, or space science, a record of excellent scholarship, and demonstrated interest in science communication, data visualization, and programming for AR/VR environments.

The initial appointment will be for one year and is renewable for a second year. Salary is highly competitive, and research and travel funding will be available. Washington University is an equal opportunity and affirmative action employer.

To apply, please contact Professor Phil Skemer (pskemer@wustl.edu), Fossett Lab Director, with a statement of interest, CV, and contact information for three references.

Biogeosciences

Employer: Louisiana State University
Position: Director of the Louisiana Geological Survey (LGS) and State Geologist (R00053299)
Location: Baton Rouge, Louisiana

The Office of Research and Economic Development at Louisiana State University invites applications for the position of Director of the Louisiana Geological Survey (LGS) and State Geologist. The individual selected for this appointment will guide existing programs in applied geosciences; build new programs that support stewardship and development of the State's natural resources; and provide the State and its citizens with geological information relevant to economic resources, environmental protection, and natural hazards. The Director will position LGS in a leadership role in such areas as coastal processes critical to the State's economy and environment; innovative approaches to natural resources: geothermal energy, oil, coal, & natural gas, raw materials, water, coastal systems; and new opportunities such as carbon capture, storage and utilization. The Director will expand upon LGS's current strengths in geological mapping, water resources, GIS and cartography, and shallow crust geophysics. The Director will hold the rank of Professor-Research (non-tenure) and will collaborate with existing geoscience-focused research programs at LSU.

The successful candidate will hold a PhD in Earth Science or a related field and a minimum of 12 years of experience post-PhD in a research setting and three (3) years supervisory experience. Questions regarding the job position can be sent to Dr. Kevin Xu (kxu@lsu.edu), Search Committee Chair. Review of applications will begin on March 1, 2021, and will continue until the position is filled. Apply or learn more about the position on the LSU Career Site bit.ly/3aInmpC.

Employer: Portland State University
Position: Postdoctoral Scholar
Location: Portland, Oregon

The Department of Civil and Environmental Engineering at Portland State University has a Postdoctoral scholar position open. The successful candidate will participate in a team-oriented project focused on developing watershed and riverine water quality transport and fate models. Duties for this position include, but are not limited to:

1) modifying and evaluating watershed and riverine water quality models;
2) developing and testing transport and biogeochemical processes of nutrients and toxic chemicals;
3) performing data analysis; and
4) developing and/or contributing to project products including reports, journal articles, and presentations.

Successful candidates will have a Ph.D. in hydrology, hydraulics, environmental engineering, chemical oceanography, biogeochemistry, or a related field. The candidate must have experience in numerical model and programming such as Fortran, Python, etc.

For further details or to apply to this position, please visit:

https://jobs.hrc.pdx.edu/postings/33507

Employer: Princeton University
Position: Research at the intersection of ocean physics and biogeochemistry
Location: Princeton, New Jersey

The AOS Program's ocean biogeochemistry group seeks energetic and enthusiastic postdoctoral or more senior researchers to participate in process-oriented studies using theory, modeling, and observations to develop understanding at the intersection of ocean physics and biogeochemistry. This effort is part of a broad study of ocean circulation, the global carbon cycle, and climate change. Of particular interest is how ocean dynamics at a range of spatial scales—from submesoscale/mesoscale fronts and eddies to regional, basin, and global scale circulations-impacts the cycling of carbon, nutrients, and oxygen, with an emphasis on the Southern Ocean.

Individuals will join a vigorous interdisciplinary research group under the direction of Professor Curtis Deutsch at Princeton University and in close collaboration with collaborators at the member institutions of the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project sponsored by NSF Polar Programs. Available resources include state-of-the-science ocean physics and biogeochemistry models and observational data sets of Southern Ocean biogeochemistry with unprecedented temporal and spatial coverage.

Candidates must have received a Ph.D. in the earth sciences, applied math, or the physical, biological, or chemical sciences. Rigorous training in oceanic sciences is preferred along with very strong dynamical, modeling, and quantitative skills. Postdoctoral appointments are initially for one year with the renewal for subsequent years based on satisfactory performance and continued funding. A competitive salary is offered commensurate with experience and qualifications.

Applicants are asked to submit a cover letter, vitae, a publication list, a statement of research experience and interests, and names of at least 3 references. Applicants should apply online to https://www.princeton.edu/acad-positions/position/19561.

Review of applications will begin as soon as they are received and continue until the position is filled. This position is subject to the University's background check policy.

Princeton University is an equal opportunity/affirmative action employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

Ocean Sciences

Employer: Princeton University
Position: Postdoc in regional ocean model development
Location: Princeton, New Jersey

The Atmospheric and Oceanic Sciences Program, in association with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), seeks a postdoctoral or more senior researcher to work in the area of regional ocean model development.

This work involves further developing the regional capabilities of the MOM6 numerical ocean model, in both a forced ocean and a fully coupled-to-atmosphere context. The candidate would focus on the development of numerical methods and algorithms in the regional version of MOM6, and would participate in the development of new regional applications to be used to address questions in predictability, climate and Earth system model down-scaling, ecosystem science and fisheries.

The ideal candidate has a strong background in one or more areas among dynamical oceanography, dynamical meteorology, applied mathematics, or numerical methods. Experience with scientific software development will be advantageous in this research.

Candidates must have a Ph.D. in either oceanography, meteorology, applied mathematics, physics, or a related field. Initial appointment is for one year with the possibility of renewal subject to satisfactory performance and available funding.

Complete applications, including a CV with a list of publications, a statement of research interests (no more than 2 pages including references), and contact information of 3 references should be submitted by March 31, 2021, 11:59 p.m. EST for full consideration. Princeton is interested in candidates who, through their research, will contribute to the diversity and excellence of the academic community. Applicants should apply online https://www.princeton.edu/acad-positions/position/19521.

For more information about the research project and application process, please contact Robert Hallberg (robert.hallberg@noaa.gov), Charlie Stock (charles.stock@noaa.gov), or Alistair Adcroft (aadcroft@princeton.edu).

This position is subject to the University's background check policy. Princeton University is an equal opportunity/affirmative action employer, and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

W	T	C				M	E	M	E		O	P	T	S
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T	O	P		C	R	O	P		O	S	I	R	I	S
V	O	L	C	A	N	I	S	M		S	N	I	P	S
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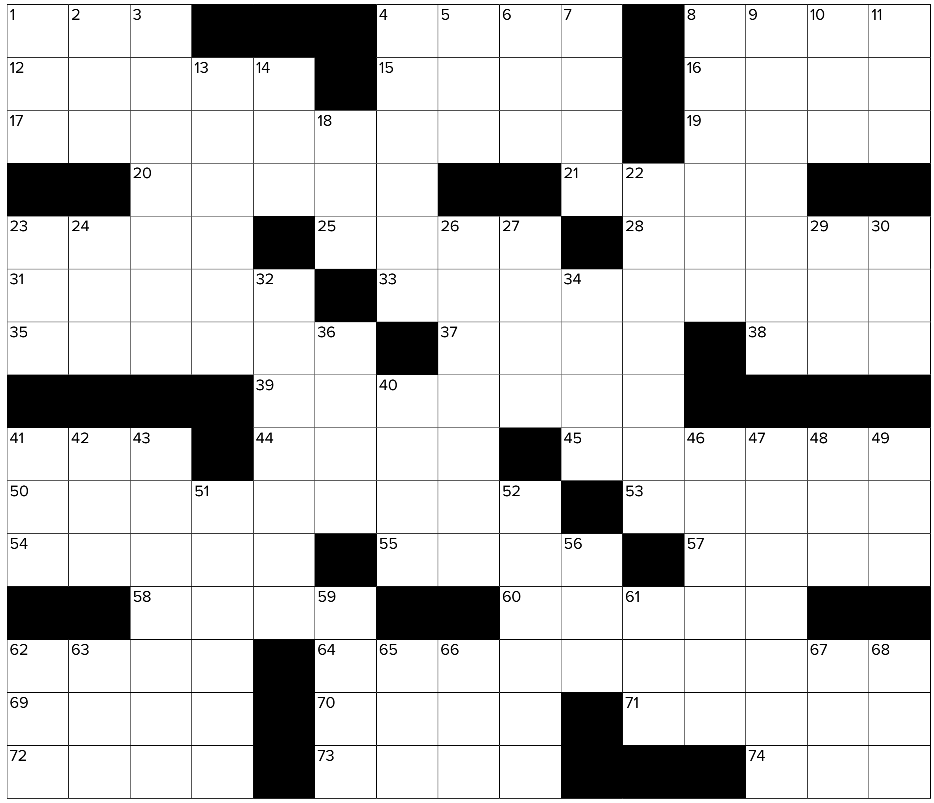
A	G	E	S		S	U	B	D	U	C	T	I	O	N
G	O	A	T		A	F	R	O		G	E	N	R	E
O	P	U	S		R	O	A	N				G	E	T

Geoprocesses

By Russ Colson, Minnesota State University Moorhead



ACROSS

1 Cmplx attacked 11 Sept. 2001
4 Child's response to the question, "Who wants some candy?"
8 Chooses
12 The baddest of the bad
15 Type of long poem
16 Unruly child
17 Geoprocess in which Earth's atmosphere interacts with crustal rock
19 Separate space in a building
20 Related to a process observed daily along coastlines
21 Feature formed by crustal processes that carry sediment across the entrance of an estuary
23 Not closed
25 Shapes of donuts—or actress Spelling
28 High-diversity continental shelf environments at risk due to climate change
31 Forward, as in "from this day ______"
33 Geoprocess in which crustal rocks are deformed by internal forces
35 Group of specialized cells in animals
37 Opposite of work hard, or baked quantity of bread
38 Healthcare provider in Great Britain (abbr.)
39 Central concept in understanding equilibrium in Earth systems, such as glacier mass ______ or atmospheric energy ______
41 Physics toy
44 Food from the Earth
45 Egyptian god of food from the Earth
50 Geoprocess common at active plate margins in which gases and molten rock emerge from the crust
53 They make little pieces
54 Like obsidian flakes
55 Not slovenly
57 Head financial executives (abbr.)
58 Shell of a one-celled creature—or a challenge in class
60 No more fish allowed
62 Geological subdivisions of periods and epochs
64 Geoprocess common near active continental margins in which crustal rock is returned to the mantle
69 Bearded, with kids?
70 High-volume hairstyle
71 Type, as of a movie or book
72 Work, as of music or art
73 Horse of a different color?
74 Procure—or understand

See **page 47** for the answer key.

DOWN

1 An information system in which documents are identified by URLs
2 Part of a glacier where the terminal moraine accumulates
3 Features formed when meteorites strike a planet
4 Bordeaux wine grape
5 Start for -dermal, -genetic, or -center
6 Time for 70 heart beats (abbr.)
7 Heart tests (abbr.)
8 Potatoes with onions and peppers
9 Amino acid chain
10 The Way, in Chinese philosophy
11 Imaging instrument that won the 1986 Nobel Prize in physics, or scanning tunneling microscope (abbr.)
13 Periods of work, as in "I had a couple of ______ as a geologist"
14 A doctorate in religious studies (abbr.)
18 Many do it three times per day
22 Start for -or and -ion, referring to jobs
23 Frequently
24 Hawaiian food made from taro root
26 Illness return
27 Venerated or representative symbol
29 Earth's first vertebrates (without the vowel)
30 Service for sending brief texts, briefly
32 Toppers for tires?
34 Beef or chicken in a shell?
36 Deserve through labor
40 Cut of meat
41 Home entertainment radio slayers of the 1950s?
42 Companion to aah
43 High, flat landscape
46 Stir up (violence)
47 Geoprocess in which crustal plates pull apart
48 First sale of company stock (abbr.)
49 Snake sound
51 Tops of mountains or waves
52 Sea salt from Essex
56 Germanic god of war
59 Russian emperor
61 Unit for small mass in medicine (abbr.)
62 Time word in *Star Wars* opening crawl
63 U.S. political party
65 Flying saucer, e.g.
66 Undergarment
67 Source material for metals
68 What's cut down after a basketball tournament